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The symposium "Milestones in Geophysics – Five Decades of Progress" was organized by The University of Texas Institute for Geophysics and held at the Lila B. Etter Alumni Center on the campus of The University of Texas at Austin on September 28 and 29, 1994. The symposium reviewed the progress in marine geophysics since 1947 and speakers addressed not only the progress achieved but the fundamental science issues that are currently being addressed. Over 200 participants attended the symposium.

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Milestones in Marine Geophysic – Five Decades of Progress

September 28–29, 1994

The University of Texas at Austin

The Office of Naval Research (ONR) provided support for the symposium "Milestones in Geophysics – Five Decades of Progress," held on September 28 and 29, 1994. The symposium was organized by The University of Texas Institute for Geophysics (UTIG) and held at the Lila B. Etter Alumni Center on the campus of The University of Texas at Austin on the occasion of the retirement of the Institute's Director, Arthur E. Maxwell. The symposium reviewed the progress in marine geophysics since 1947, and speakers described not only the progress achieved but the fundamental science issues that are being addressed. Over 200 participants attended.

The first days speakers included Gustaf Arrhenius of Scripps Institution of Oceanography who recounted the original attempts to measure heat flow during the Swedish Deep Sea Expedition of 1947-48. Richard P. Von Herzen of Woods Hole Oceanographic Institution reviewed the results of DSDP Leg 3 where he and his co-chief scientist, Arthur Maxwell, drilled a series of deep holes across the mid Atlantic ridge and recovered the first direct geologic evidence that confirmed the theory of sea floor spreading. John Knauss, recently retired administrator of NOAA, reflected on the initial development of the ocean drilling program which has proved fundamental to the advancement of marine geology and geophysics since its formation.

The role of Arthur Maxwell during the early years of the ONR is well known and was recounted during dinner by Ned Ostenso, Assistant Administrator, Office of Oceanic and Atmospheric Research, NOAA. Earlier, during the first days formal presentations, Fred Saalfeld spoke about the changes in direction and organization that the ONR is undergoing during the 1990's to be more effective and relevant to the Navy's mission. The positive and sustaining role of the ONR in the field of marine geophysics is well recognized and Saalfeld's presentation provided guidance to researchers in the field.

Education in the field of marine geophysics has benefited from Arthur Maxwell's involvement since his days at the Woods Hole Oceanographic Institution and then subsequently at The University of Texas at Austin. Lawrence Peirson, reviewed the establishment of the Massachusetts Institute of Technology/Woods Hole Oceanographic Institution joint program, and the role that Arthur Maxwell played in the establishment of this ongoing and successful education program. After coming to The University of Texas as the Director of the Institute for Geophysics, Arthur worked closely with the Department of Geological Sciences and Texas A&M University. William, J. Merrell reminded the attendees of the history of oceanography in Texas and the role of the UTIG from its early formative days under the direction of Maurice Ewing through Arthur Maxwell's careful stewardship. Milo Backus of the Department of Geological Sciences showed the tremendous impact that Arthur Maxwell had on the education program in marine geophysics at The University of Texas at Austin by reviewing the growth in the number of students awarded degrees and their research contributions.

During the second day's activities, presentations focused on current and future research programs in marine geophysics. Poster papers presented by UTIG faculty and students from the Department of Geological Sciences covered topics from plane wave migration and imaging techniques to marine geology, geophysics and structural interpretations from: southeast Australia, the northern Barbados ridge, and the Bransfield

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Strait of Antarctica among others. Analysis techniques applied to geophysical data, including neural networks, genetic algorithms, and modern sampling techniques were also presented.

The formal presentations of the second day of the symposium were principally by UTIG scientists. James Austin discussed high-resolution 2D and 3D shallow seismic surveying with coring comparisons on the continental shelf and Thomas Shipley described the use of 3D seismics to obtain images of the complex geologic structures of convergent margins. Mike Coffin considered the origin of large igneous provinces from oceanic plateaus to volcanic passive margins and Ian Dalziel speculated on the fundamental role of plate tectonic cycles. Jan Garmany reported on a new model for the delivery of magma to mid-ocean ridges, based on recent ocean bottom seismic data, while Dan McKenzie described the role of mantle convection on the planetary scale by comparing the earth and Venus.

The extended abstracts of the second day's presentations follow. The participants in the symposium are listed in the appendix. The program presented at the symposium which includes the abstracts of the presentations including the poster papers, and a brief review of Arthur E. Maxwell's scientific achievements is included.

High-Resolution 2-D and 3-D Seismic Surveying and Coring on the New Jersey Outer Continental Shelf

James A. Austin, Jr., Thomas A. Davies, Craig S. Fulthorpe, The University of Texas at Austin, Institute for Geophysics; Martin B. Lagoe, The University of Texas at Austin, Department of Geological Sciences and Institute for Geophysics

ABSTRACT

The nature and distribution of late Quaternary periglacial sediments, the history of post-Wisconsin sedimentation, and the relationships of late Pleistocene to earlier sequence stratigraphy offshore New Jersey are the foci of ongoing studies using both Huntec® deep-towed seismic reflection profiling and coring and multichannel seismic (MCS) reflection profiles collected by industry. Available 2-D seismic surveys delineate two late Quaternary sediment wedges, one occupying the mid-shelf and another extending south from the Hudson apron along the shelf edge. A 1989 3-D Huntec survey of the outer-shelf wedge, combined with piston and gravity coring, has revealed prominent, mappable reflectors, one of which delineates a system of meandering channels apparently draining obliquely (southward) toward the shelf edge. A 1993 Huntec survey has acquired additional regional/2-D and 3-D profiles across portions of both outer- and mid-shelf sediment wedges, along with vibra-cores. The 1993 profiles show more than one channeled surface within the wedges, confirming the occurrence of multiple erosional episodes during their formation. All of the Huntec and core control is nested within an available and extensive grid of older, low-frequency industry MCS profiles. A high-resolution MCS survey planned for 1995 is a component of the STRATAFORM (STRATA FORmation on Margins) initiative of the Office of Naval Research (ONR). This field program will include hazards-type surveys of proposed Ocean Drilling Program shelf sites, setting the stage for completion of a transect of boreholes from the New Jersey Coastal Plain to the continental slope.

BACKGROUND

Along the edge of the continental shelf off New Jersey, seismic reflection surveys have delineated a wedge of late Quaternary sediment extending south from the Hudson apron (Fig. 1). The bottom of this sediment wedge is defined by a prominent seismic reflector ("R"), which has been interpreted to represent an erosional surface formed during the last low-stand of sea level (i.e., at Wisconsin Maximum). A 3D survey conducted by UTIG in 1989 was designed to address very subtle changes in the regional seismic stratigraphy of that wedge. The survey instrument was a Huntec DTS® (deep-towed seismic acquisition) system, purchased by ONR and operated by Woods Hole Oceanographic Institution (WHOI). Shot spacing was 2.5 m; repetition rate was 1 sec (ship's speed nominally 5 kts). The survey covered a rectangle 5 km (E-W) x 0.5 km (N-S), consisting of 50 E-W lines each ~5.0 km long. Line spacing was ~10 m, maintained using Starfix®, a precision navigation system with accuracies of ~5 m. The Huntec fish was towed at a depth of ~30 m so that subbottom data above R would not be contaminated with ghost arrivals. Recording was digital; sampling rates were 0.1 msec on input data filtered at 500-3,500 Hz.

A second Huntec survey, conducted in the same general area in 1993, acquired additional regional/2-D and 3-D profiles along with a suite of vibra-cores. Both 1989 and 1993 3-D grids were located within a regional framework of E-W Huntec profiles, spaced 1 nmi apart (Fig. 2). The 1993 3-D grid was also positioned to image portions of both outer- and mid-shelf sediment wedges (compare Fig. 1 and Fig. 2).

All of the Huntec data have been collected within an enormous regional grid of industry MCS profiles collected in the 1970's (Fig. 2). These data, acquired on digital tape and redisplayed on workstations at UTIG, are being used to tie the high-resolution Huntec results to older (i.e., Neogene), more deeply-buried sequence stratigraphy imaged at lower frequencies along the outer shelf and slope. The Middle Atlantic Transect (MAT) of proposed

Ocean Drilling Program (ODP) boreholes to study sea level objectives on the shelf also passes through both the Huntec and industry MCS control. ODP Leg 150 drilled sites 902-906 on the upper slope in 1993 (Fig. 2).

RESULTS

The 1989 Huntec survey, combined with results from piston and gravity coring, has revealed two prominent, mappable reflectors between R and the sea floor. The upper reflector delineates a system of meandering channels apparently draining obliquely (southward) toward the shelf edge (Fig. 3). Correlation with late Quaternary glacial history developed from studies on land suggests that R is an erosional surface formed at the last lowstand of sea level and that the outer-shelf wedge has formed from a series of rapid depositional events related to post-Wisconsin maximum stages of glacial melting, interrupted by one or more erosional episodes as implied by the channels (Davies et al., 1992).

Preliminary examination of the 1993 Huntec profiles shows more than one channeled surface within the sediment wedges, confirming the occurrence of multiple erosional episodes during their formation. Vibra-cores have confirmed that the core of the outer wedge, into which channels are cut, consists of stiff, sparsely fossiliferous silty clay with a fauna indicative of mid-shelf depths. By contrast, channels in the mid-shelf wedge are cut into medium-coarse sand in which shell fragments are rare or absent, then filled with silty clay having an estuarine fauna. The clay is in turn overlain by sand rich in shell fragments. Both sands contain mid-shelf benthic foraminiferal faunas. Physical properties (velocity, bulk density) measurements on the cores made at the University of Colorado will permit further calibration of the Huntec records, while biostratigraphy and AMS C-14 dating in progress at WHOI should establish environmental history and chronology.

FUTURE CORRELATIONS

The late Quaternary sedimentation history being developed using the Huntec profiles and coring results can be linked to the older (deeper) Pleistocene and pre-Pleistocene shelf record by using MCS records of varying seismic resolution along with results of recently completed (Leg 150) and proposed ODP shelf drilling (Fig. 2). The comparatively low-resolution, but extensive grid of industry MCS data is currently being interpreted and mapped (Fig. 2), in conjunction with ongoing work on the Huntec data. A high-resolution MCS survey is planned for 1995 as a component of the STRATAFORM (STRATA FORmation on Margins) initiative of the Office of Naval Research (ONR) (Fig. 4). The goal of STRATAFORM is to understand the creation of the stratigraphic record on continental shelves and slopes as the product of geological processes. The planned field program will also incorporate hazards-type surveys of a number of proposed ODP shelf drill sites (Fig. 5), setting the stage for eventual completion of a transect of boreholes from the New Jersey Coastal Plain to the continental slope. The Coastal Plain and slope components of the transect have already been drilled (ODP Legs 150X and 150, respectively).

ACKNOWLEDGMENTS

This work is funded by the Office of Naval Research, with supplemental support for high-resolution surveys in the vicinity of proposed ODP shelf sites from the National Science Foundation, through the U.S. Science Support Program of ODP administered by Joint Oceanographic Institutions, Inc.

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Davies, T.A., Austin, J.A., Jr., Lagoe, M.B., and Milliman, J.D., 1992, Late Quaternary sedimentation off New Jersey: New results from 3-D seismic profiles and cores: Marine Geology, **108**, 323-344.

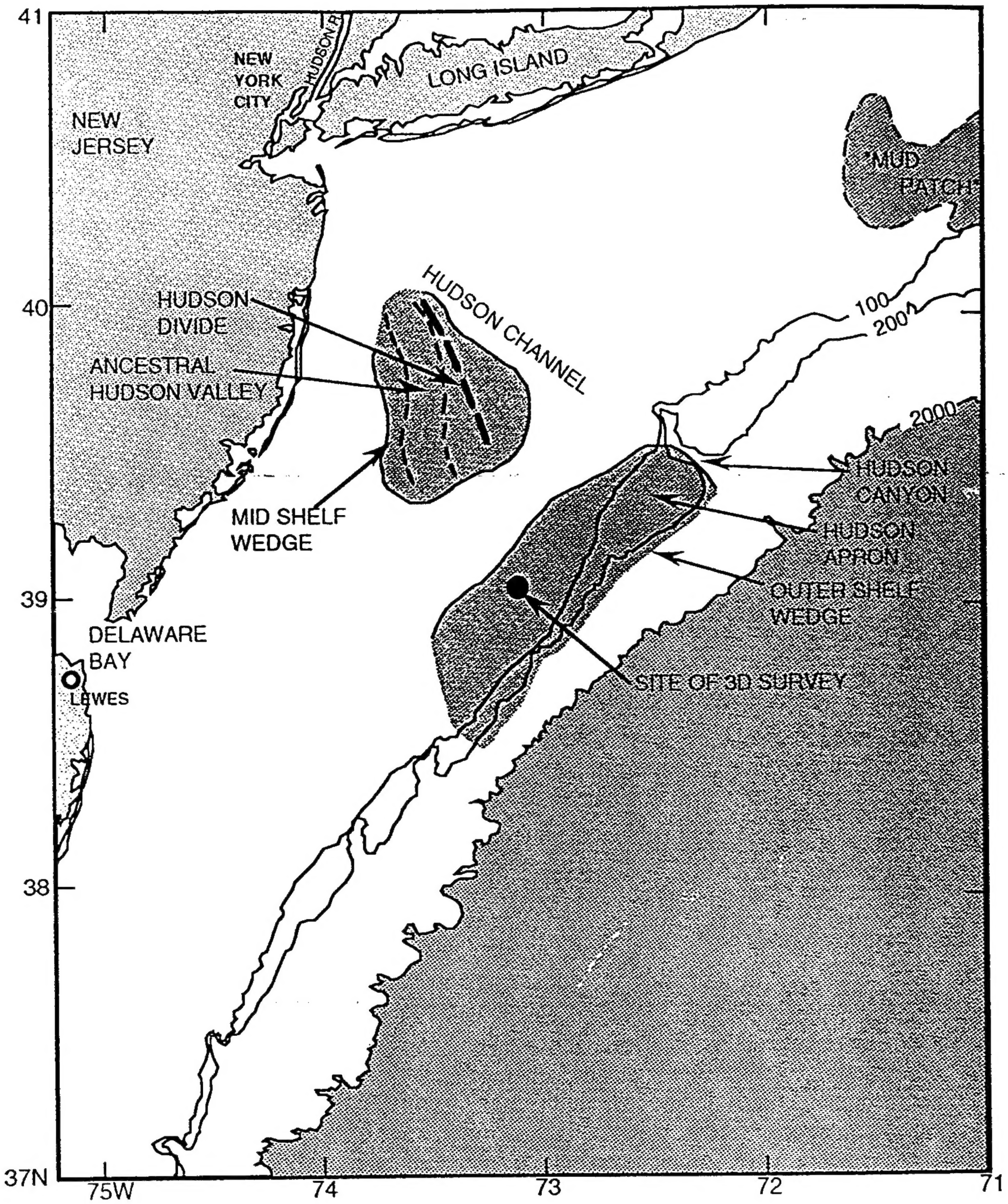

FIG. 1. Map showing relationships of the mid- and outer shelf late Quaternary sediment wedges offshore New Jersey. Approximate location of the 1989 Huntec 3D survey is shown. The 1993 Huntec 3D survey straddled the boundary between the two wedges (see also Fig. 2).

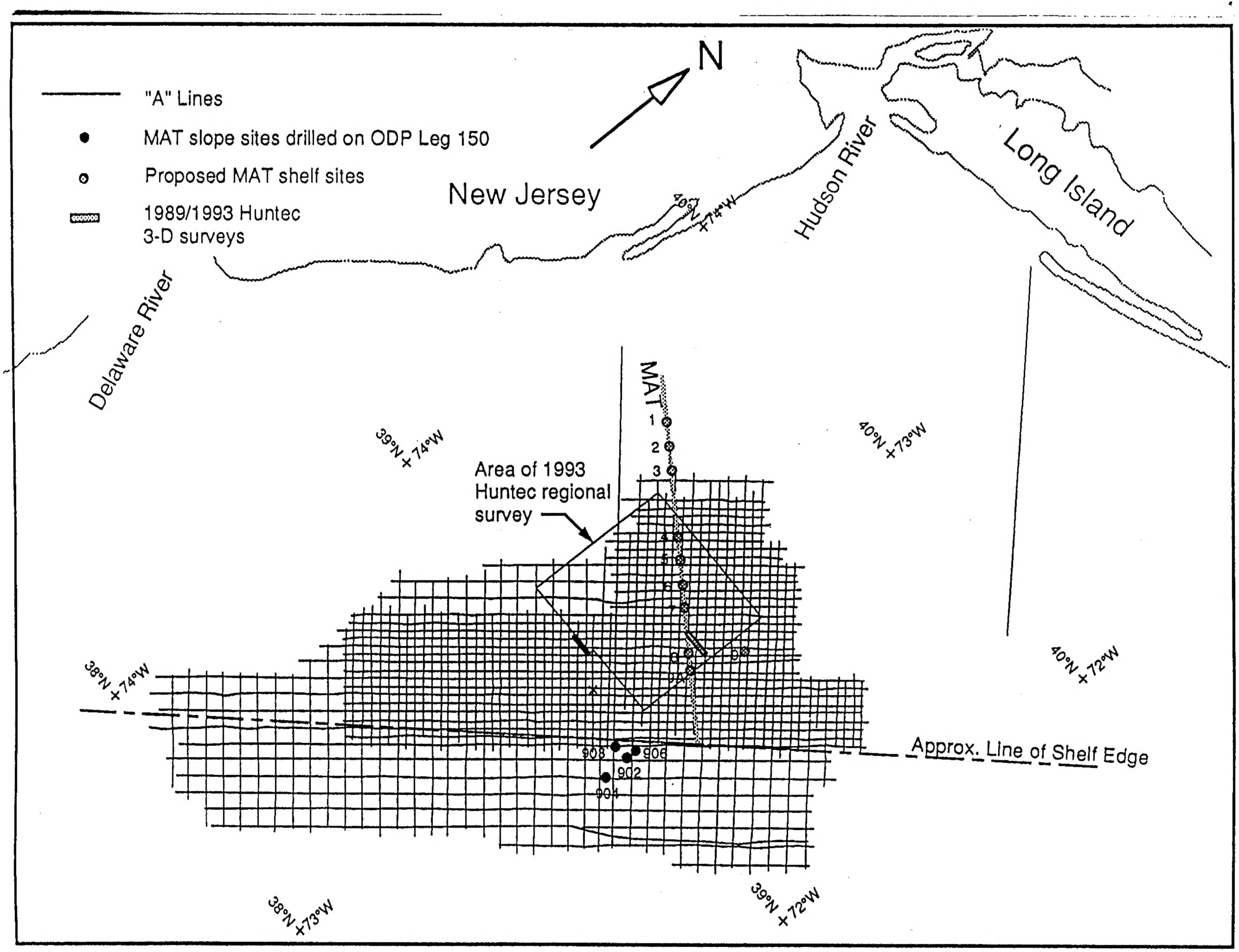

FIG. 2. Location map showing oil industry seismic data, 1989 and 1993 Huntec surveys, proposed Middle Atlantic Transect (MAT) shelf drill sites and MAT slope sites drilled during ODP Leg 150.

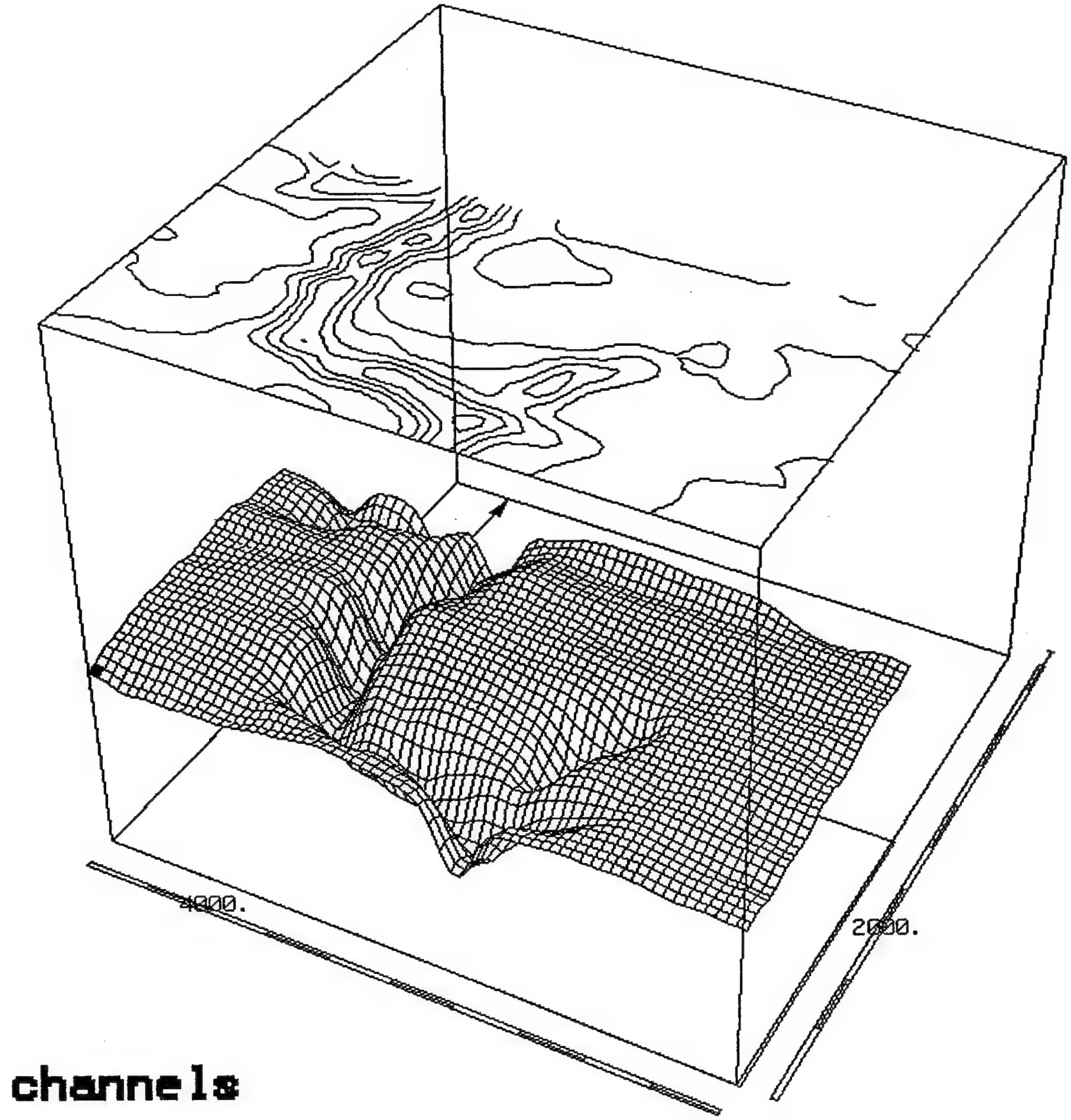

FIG. 3. A representation of a channeled surface on the New Jersey outer continental shelf, as imaged by 3-D Huintec profiling. The channel has been filled with sediment and is now shallowly buried beneath the shelf surface. Contour interval of the map of the surface superimposed on the top of the cube is in ms (1 ms ~0.75 m at water velocity). Total relief of the channel is therefore ~4 ms (3 m). Divisions on horizontal scales each represent 100 m. Arrow at the base of the cube denotes northerly direction.

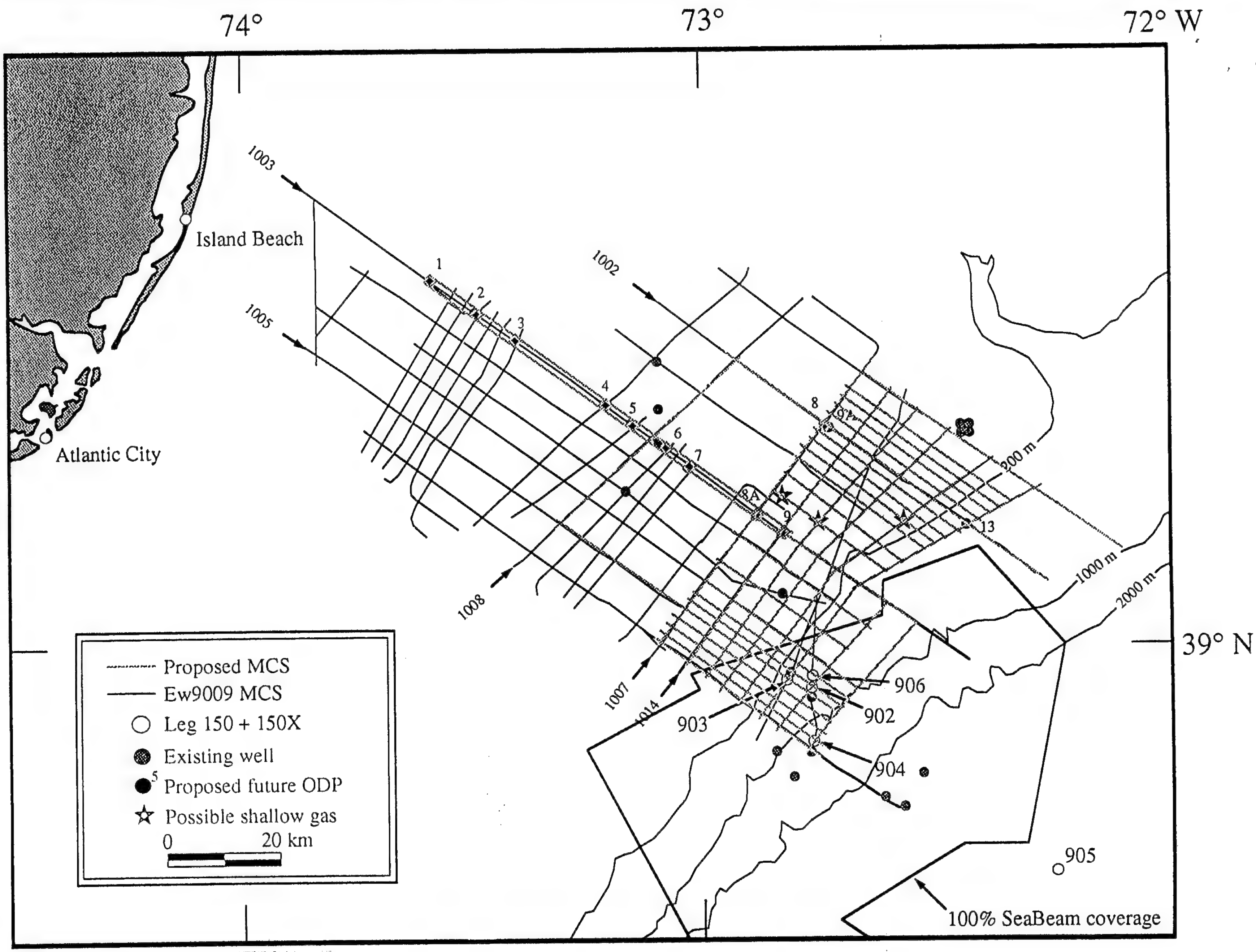

FIG. 4. High-resolution MCS profiling proposed for FY 1995 using the WHOI vessel *Oceanus* and a commercial seismic system. Specific profiles from preexisting MCS survey *Ewing* 1009 (used for choosing MAT sites) are indicated for reference. For details of hazards surveys to be conducted at MAT/proposed ODP shelf sites, refer to FIG. 5.

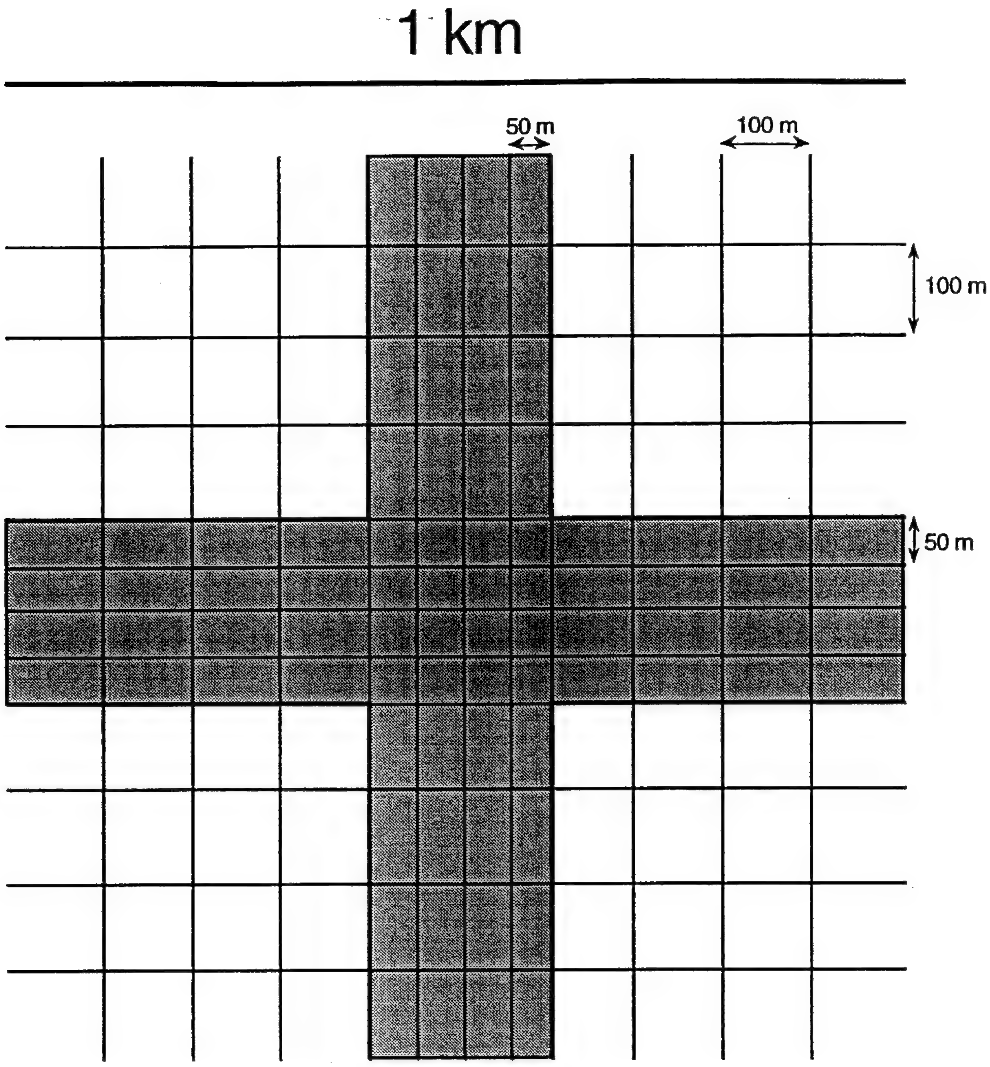

FIG. 5. Detail of "hazards" survey grid as stipulated by the Shallow Water Drilling Working Group report to JOIDES (1994).

Large Igneous Provinces: A Perspective from Oceanic Plateaus and Volcanic Passive Margins

Millard F. Coffin, Institute for Geophysics,The University of Texas at Austin

Large igneous provinces (LIPs) are massive crustal emplacements of predominantly mafic (Mg and Fe rich) extrusive and intrusive rock which originate via processes other than "normal" seafloor spreading. Physical manifestations of mantle processes, these global phenomena include continental flood basalts, volcanic passive margins, oceanic plateaus, submarine ridges, seamount groups, and ocean basin flood basalts (Figure 1). Study of LIP-forming processes has intensified over the past five years as new information has become available from seismic tomography, geochemistry, marine geophysics, petrology, and geodynamic modeling, among other geoscientific disciplines (e.g., Coffin and Eldholm, 1994). Furthermore, recent research has documented important temporal, spatial, and compositional similarities among various LIPs.

LIPs are globally significant. After basalt and associated intrusive rock emplaced at spreading centers, LIPs are the most significant accumulations (10^5 - 10^6 km^3) of mafic material on the Earth's surface. They are commonly attributed to mantle plumes or hotspots, and presently account for between 5% and 10% of the heat and magma expelled from the mantle. However these fluxes are not distributed evenly in space and time; their episodicity punctuates the relative steady-state production of crust at seafloor spreading centers. LIPs, therefore, provide windows into those regions of the mantle which do not generate normal mid-ocean ridge basalt (N-MORB). Seismic tomography suggests that velocity structure beneath mid-ocean ridges is different than that beneath hotspots, implying shallower, passive upwelling beneath ridges and deeper, dynamic upwelling beneath hotspots. Furthermore, thermal structure of the upper mantle is heterogeneous, suggesting that extensive magmatism requires a combination of hot upper mantle and suitable lithospheric conditions. Despite a wealth of data and results on hotspots and mantle plumes (for reviews and syntheses see White and McKenzie, 1989; Duncan and Richards, 1991; Hill et al., 1992; and Sleep, 1992, among others), none of the available models satisfactorily explain the genesis of all LIPs or even individual categories of LIPs.

LIPs are distributed world-wide, occurring on both continental and oceanic crust in purely intra-plate settings, on present and former plate boundaries, and along the edges of continents (Figure 1). Continental flood basalts, the most intensively-studied LIPs, are predominantly tholeiitic magmas erupted on continental crust over time scales of 10^5 to 10^6 years. Generally believed to be the product of fissure eruptions, they consist primarily of horizontal and subhorizontal flows. Volcanic passive margins, situated on the trailing, rifted edges of continents are characterized by excessive volcanism, and uplift and/or lack of rapid initial subsidence, during continental break-up. Margin formation is associated with both intrusive and extrusive activity. The oldest oceanic crust is thicker than adjacent "normal" oceanic crust, and the lower crust beneath the extrusives is commonly characterized by bodies with high seismic velocities.

In deep ocean basins, the largest LIPs are oceanic plateaus, broad, more or less flat-topped features which generally lie 2000 m or more above the surrounding seafloor. They are formed by mafic volcanism and associated intrusive activity; their extrusive cover may be emplaced either in subaerial (e.g., Kerguelen Plateau) or submarine (e.g., Ontong Java Plateau) environments. Oceanic plateaus are commonly isolated from major continents. Their crustal thickness is anomalously greater than that of adjacent oceanic crust, and their age may or may not be similar to that of adjacent crust. Another category of oceanic LIP is submarine ridges, which are elongated, steep-sided elevations of the seafloor. They may be of continental or oceanic origin, and we only consider the latter herein. Submarine ridges are commonly characterized by varying topography, and those of basaltic nature may be created either on or off the axes of spreading centers. As with oceanic plateaus, their volcanic upper crust may be emplaced either subaerially or

under water. Closely related to submarine ridges are seamounts, which are local elevations of the seafloor. Seamounts are flat-topped (guyot) or peaked mafic volcanoes whose last stages of construction were in a subaerial or a submarine environment, respectively. They may be discrete, arranged in a linear or random grouping, or connected at their bases and aligned along a ridge or rise. The least-studied LIPs are ocean basin flood basalts, which are thick, extensive submarine flows and sills lying above and post-dating oceanic igneous basement. Recently K. Hinz [pers. comm., 1992] has discovered thickened oceanic crust and dipping intra-basement reflectors in deep ocean basins with linear seafloor spreading-type magnetic anomalies. We term this crustal type anomalous seafloor spreading crust.

LIPs are found in a variety of tectonic settings including the axes of seafloor spreading centers (e.g., Iceland), triple junctions (e.g., Shatsky Rise), old oceanic lithosphere (e.g., Hawaii), passive margins (e.g., North and South Atlantic volcanic margins), and cratons (e.g., Siberian Traps). Those situated at spreading centers, such as Iceland, Azores, and Galapagos, are readily distinguishable from "normal" oceanic crust by their anomalous volumes and geochemical signatures. Recent discussion has focused on whether mantle plumes and plate tectonics operate largely independently or are intimately linked; no consensus has been reached.

LIPs which are indisputably emplaced at plate boundaries include those now observed to lie on active spreading centers, those which are reliably dated to be the same age as adjacent "normal" oceanic crust, and volcanic passive margins. As higher quality seismic reflection data become available on passive margins, an increasing number appear to be "volcanic"; thus massive volcanism may be quite common when continents separate. Many LIPs, however, are difficult to associate with plate separation. Part of the reason is that most oceanic crust is Cretaceous or younger; nearly all older oceanic crust with accompanying LIPs has been subducted. This makes tying older LIPs to younger LIPs or presently active hotspots difficult. The paucity of hotspot tracks on continents, however, could suggest that plate separations produce favorable conditions for thermally anomalous mantle to upwell. Alternatively, continental lithosphere might be robust enough to deflect all but the most vigorous mantle upwellings to oceanic areas.

Given the potential characteristics required for a mantle upwelling to reach the surface and form a LIP - size of the mantle upwelling, its temperature, and its temporal variability, as well as the heterogeneous vulnerability of the lithosphere - it is remarkable that hotspot trails are in some cases traceable over 100+ m.y. It further implies that the long-lived tracks, including those emanating from Hawaii, Kerguelen, Réunion, Iceland, and Tristan da Cunha, are among the most stable and vigorous.

Evidence that LIPs both manifest a fundamental mode of mantle circulation commonly distinct from that which characterizes plate tectonics, and contribute episodically, sometimes catastrophically to global environmental change is accumulating rapidly. Dating of many continental flood basalts, from the Deccan Traps in particular, have convincingly shown the geological suddenness of LIP emplacement. Geophysical and drilling data have demonstrated in one case, the North Atlantic Volcanic Province, that a large volumetric percentage of those continental flood basalts associated with continental break-up lie offshore, that the uppermost extrusives were erupted subaerially, and that the intrusive component of LIPs is at least as voluminous as the extrusive component. Geophysical and drilling data from two oceanic plateaus, Ontong Java and Kerguelen-Broken Ridge, have illustrated that volumetrically these LIPs dwarf all others known, that much of Kerguelen's uppermost crust was erupted subaerially, and that extrusives of the Ontong Java LIP affected ~1% of the Earth's surface. However, the data base, particularly with respect to deep crustal structure and drillholes providing reliable age, compositional, dimensional, and environmental data with which to formulate and constrain geological models, is significantly smaller than for most other comparable on- and offshore features. It is important to recognize that to date we have literally only scratched the surface of offshore LIPs. Nevertheless, the relative scale of LIPs and the large dimensions of some LIPs are certainly real, whereas absolute values will undoubtedly change with new data.

The dimensional analysis of Coffin and Eldholm (1994), combined with seismological, geochronologic, geochemical, and isotopic data

and results, supports a complex model of mantle circulation. Plumes responsible for the largest igneous provinces likely originate from the D" layer at the base of the mantle. Smaller plumes may well originate in the transition zone between the lower and upper mantle. How plumes at any scale interact with primary plate tectonic mantle convection, and why some relatively weak plumes should persist for 100 m.y. or more remain very much open questions. The heterogeneous thermal character of the mantle, the presence of at least four distinct mantle reservoirs, and the two fundamental modes of mantle circulation suggest a complexity beneath our feet which will occupy geoscientists' attention well into the future.

Tectonic contributions to global change are increasingly being recognized. Episodic geometrical, chemical, and physical changes accompanying LIP emplacement would potentially affect the hydrosphere and atmosphere; LIPs which form when the global environment is in or near a "threshold" condition, e.g., the North Atlantic Volcanic Province near the Paleocene-Eocene boundary, can potentially push the planet over the threshold. In this context the mid-ocean ridge system is viewed as more a "regulator" and LIPs more an "instigator" of global environment change.

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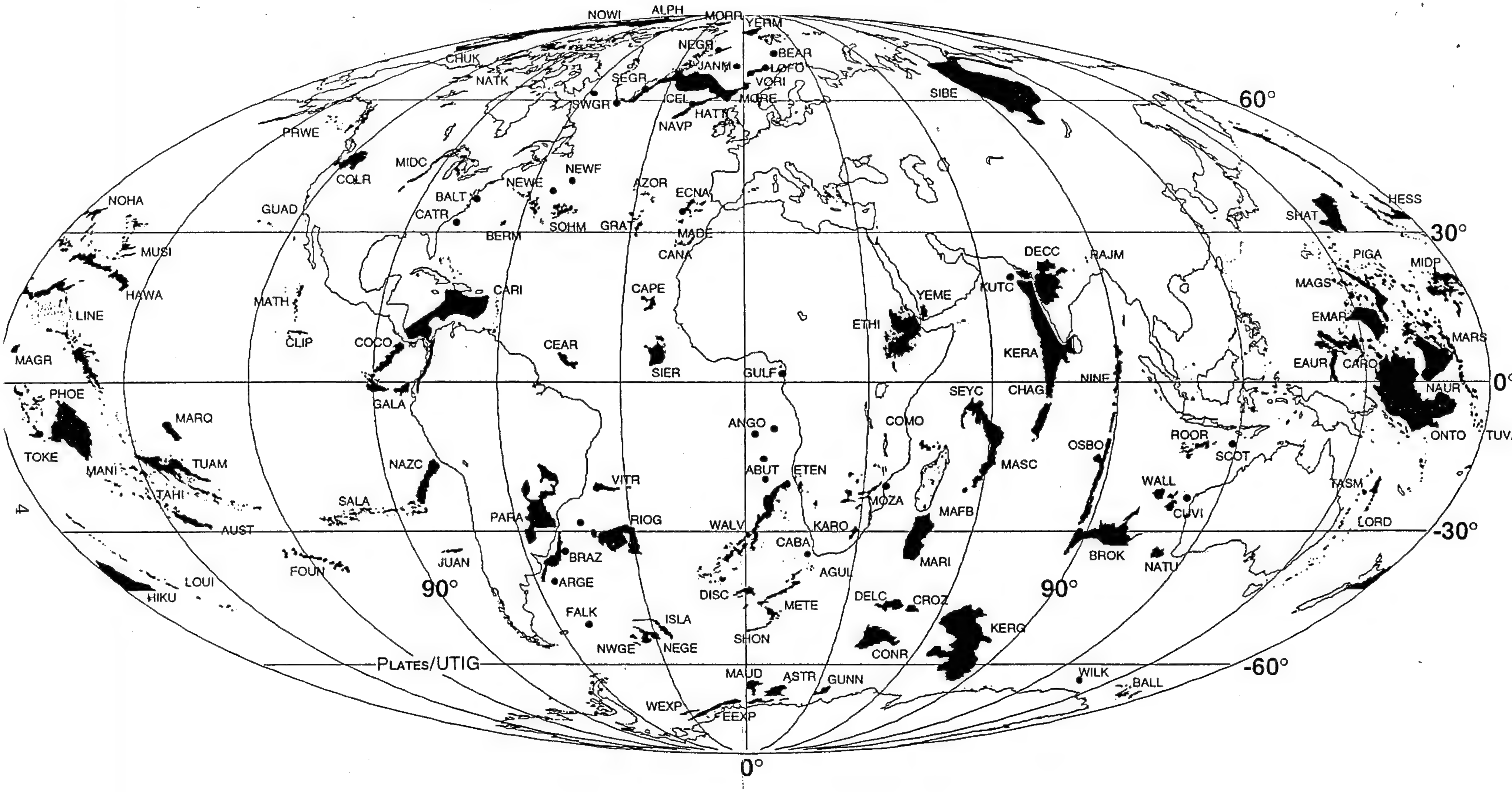

FIGURE 1

Figure 1. Global LIPs, including continental flood basalt and associated intrusive provinces; volcanic passive margins; oceanic plateaus; submarine ridges; ocean basin flood basalts; and seamount groups. Filled circles indicate volcanic passive margins where seaward dipping reflector sequences have been recognized. See Coffin and Eldholm (1994) for key to abbreviations. Digital map courtesy of the PLATES Project (Institute for Geophysics, The University of Texas at Austin).

Are Plate Tectonic Cycles Real?: Rechecking The "Pulse Of The Earth"

Ian W. D. Dalziel, Institute for Geophysics, The University of Texas at Austin

LAURENTIA

The ancestral core of the North American continent was assembled by collisional tectonic processes by ca. 1.0 Ga (Hoffman, 1988). However, although the location of North America on earth's surface can be convincingly established as far back as the Mesozoic opening of the Atlantic Ocean basin on the basis of marine geophysical data (Klitgord and Schouten, 1986), the origin of Laurentia as a discrete continent has remained obscure because it is surrounded by Neoproterozoic to Cambrian rift systems (Hoffman, 1989). Within Pangea it is a "suspect terrane" of uncertain prior geographic position (Coney et al., 1980). Conventionally Laurentia has been positioned opposite northwest Africa in Paleozoic reconstructions, reflecting J. Tuzo Wilson's question: "Did the North Atlantic open, close, and then reopen?" (Wilson, 1966). It has also been conventional to restore the Appalachian margin of the Laurentian craton against northwestern Africa in late Precambrian reconstructions (e.g., Hatcher, 1989). There is, however, no firm geologic evidence for this reconstruction, and paleomagnetic data afford no longitudinal control. Thus, alternative reconstructions are permissible as long as they can account for observations such as the distribution of Avalonian rocks along margins of North America, Europe, and Africa and the presence of Rokelide (?) basement and fossiliferous Paleozoic cover beneath the Coastal Plain of northern Florida (Hatcher et al., 1989). The rifted counterpart of the Pacific margin of the Laurentian craton is also obscure. Sears and Price (1978) suggested rifting from part of Siberia during the mid-Proterozoic. Bell and Jefferson (1987) drew attention to the similarity of the Neoproterozoic strata of western Canada and eastern Australia, and suggested that they had been juxtaposed at that time, although no reconstruction of the cratons themselves was presented.

One of the linchpins of Du Toit's reconstruction of the Gondwana supercontinent prior to the opening of the southern oceans was the truncation of the early Mesozoic Cape fold belt at the Atlantic margin of southern Africa, and its apparent continuation in the Sierra de la Ventana that is truncated along the Atlantic margin of South America (Du Toit, 1937). The truncation of the Appalachian and Caledonian orogens along the margins of the North Atlantic provide similar evidence in support of Mesozoic separation of North America and Europe (Holmes, 1945; Kay, 1969). The termination of the Grenville orogen of Laurentia at the Labrador margin also appears to be explained by the presence of the Sveco-Norwegian province of the same age in the Baltic craton, although the connection through northern Britain is somewhat tenuous (Gower and Owen, 1984; Gower et al., 1990). In contrast, the termination of the Grenville and adjoining Yavapai-Mazatzal orogens at the Pacific margin of the Laurentian craton has lacked an obvious explanation, despite the presence of some Grenvillian-age rocks in northwestern South America (Dengo, 1985). Recently, however, Moores (1991) broke new ground by presenting a reconstruction with the East Antarctic-Australian craton juxtaposed with that of Laurentia in the Neoproterozoic. Dalziel (1991) supported this with a computer reconstruction and identified a possible counterpart for the Yavapai/Mazatzal-Grenville boundary, the Grenville front, near the head of the Weddell Sea embayment. These developments led to new theories regarding the configuration of a possible Neoproterozoic supercontinent (Dalziel, 1991 and 1992; Hoffman, 1991).

Another potential "piercing point" (Crowell, 1959) along the margin of the Laurentian craton is provided by the southern termination of the Appalachian orogen. The effects of the collision of Laurentia with Africa to form Pangea are visible in the Ouachita orogeny and the terminal Alleghanian event of the Appalachian orogenic revolution (Hatcher et al., 1989), although the main Appalachian mountain range and the Ordovician structures of the Taconic orogen disappear southwestward beneath the Gulf of Mexico Coastal Plain. Again, until recently, this apparent truncation

and the "hole" in the North American continent represented by the Ouachita embayment have remained unexplained. Dalla Salda et al. (1992a, 1992b) have suggested that the continuation of the Taconic orogen is to be found in the Famatinian belt of South America and possibly even further south in the Shackleton Range of East Antarctica. Thus several lines of evidence point to the possibility that, within Pangea, North America was an "exotic terrane" of intra-Gondwanian affinities that had traveled nearly 10,000 km along the proto-Andean margin of South America during the Paleozoic (Dalziel, 1991, Fig. 2; Dalziel et al., 1992).

GONDWANA

The North American affinities of the Precordilleran terrane that borders the present-day Andes of northwestern Argentina has been known for many years (Borrello, 1971; Ross, 1975; Ramos et al., 1986). Its Cambrian-Ordovician carbonate platform contains the Pacific realm Olenellid trilobite fauna of Walcott (1889). The presence of this fauna, and determination of a thermal subsidence curve that indicates rift-drift transition close to the Precambrian-Cambrian boundary, led Bond et al. (1984) to suggest that the proto-Appalachian and proto-Andean margins were juxtaposed in the late Precambrian. Recently Hoffman (1991) and I (Dalziel, 1991, 1992) used the same criteria, and the presence of a 1.3 - 1.0 Ga "Grenvillian" age orogen on the western margin of the Transamazonian craton, to put forward similar hypotheses that Laurentia originated between East Antarctica-Australia and the Precambrian cratons of embryonic West Gondwana prior to the Neoproterozoic opening of the Pacific Ocean basin and amalgamation of the Gondwana supercontinent. The Paleozoic Famatinian belt, however, intervenes between the Precordilleran terrane and the Gondwana craton. Therefore, Dalla Salda et al. (1992b) have suggested that the carbonate platform was part of the interior of the Laurentian craton that was detached from the Ouachita embayment following collision with the South American margin of Gondwana during the Ordovician Taconic-Ocloyic (i.e. early Famatinian) orogeny (Dalla Salda et al., 1992a). Hoffman (1992) and I (Dalziel, 1992) both believe, on the basis of time-space considerations, that western Laurentia must have separated from the Pacific margin of East Antarctica-Australia in mid-Proterozoic (Windermere-?Beardmore) time. Paleomagnetic data, indicate that Laurentia may have stayed close to the proto-Andean margin of South America during the late Precambrian opening of the Pacific Ocean basin and amalgamation of the Gondwana supercontinent, and during the Paleozoic (Dalziel, 1991, Fig. 2; 1992). Thus, the "south-east Pacific continent" that students of South American geology have, for many years, considered to have lain off the Andean margin of Gondwana during the Paleozoic (e.g., Dalmayrac et al., 1980), may have been Laurentia.

A LAURENTIA-SOUTH AMERICA FIT

The Appalachian margin of Laurentia has well developed promontories and reentrants that are believed to reflect the configuration of the craton margin following Neoproterozoic rifting (Williams, 1964; Thomas, 1977, 1991; Hatcher et al., 1989). The most obvious promontory along the margin of the Laurentian craton, however, is located at the northern termination of the Appalachian orogen. I shall refer to this as the Labrador-Greenland promontory (Fig. 1). Although the present-day margin of southeastern Greenland resulted from Mesozoic rifting of Europe from North America, the presence of the craton margin in northwesternmost Scotland and central East Greenland indicates that this promontory must have been at least as pronounced at the end of the Precambrian as it is today. There is considerable similarity between the geology of the Baltic craton and that of northeastern Labrador and Greenland. Thus in late Precambrian reconstructions, Baltica is usually restored to a position adjacent to the Labrador-Greenland promontory with an adjustment of relative orientation (Gower and Owen, 1984; Gower et al., 1990), although this is not necessarily the pre-Iapetus position. There is no reason why another, geologically similar, cratonic area could not have intervened.

The late Precambrian proto-Andean margin of the Amazonian craton can be identified in northernmost Argentina (Fig. 1). The Neoproterozoic to lower Cambrian Puncoviscana Formation mainly comprises turbidites derived from the craton (Aceñolaza et al., 1988; Jesek et al., 1985), but it also con-

tains shallow water sedimentary strata with fossils comparable to those found in the southwestern United States (Aceñolaza and Durand, 1986). There is therefore, despite limited exposure of the basement and overprinting by Andean orogenesis, evidence that these rocks may represent the remnants of a late Precambrian margin.

Tracing the Pacific limit of this margin yields what may be a critical clue to its origin. To the south it forms the boundary between Rio de la Plata craton and the Paleozoic Famatinian orogen (Dalla Salda et al., 1992a). To the north and west lies the Arequipa massif along the coastline of southern Peru that has puzzled students of Andean geology for many years. Located immediately to the north of the prominent Arica bight in the present-day continental margin, the Arequipa massif comprises high-grade metamorphic rocks (granulite facies) that yield radiometric dates on the order of 2.0 Ga (Cobbing et al., 1977; Dalmayrac et al., 1977). Its presence outboard of the Andean Cordillera has led several authors to suggest that it may constitute an exotic terrane that collided with South America, thereby contributing to orogenic uplift of the Cordillera in general and the Altiplano in particular (e.g., Nur and Ben-Avraham, 1982). Stratigraphic evidence, however, indicates that the Arequipa massif has been in essentially its present position along the Andean margin since the late Precambrian to early Paleozoic (Forsythe et al., 1992), and the Cordillera appears to be ensialic (Dalmayrac et al., 1980). The ca. 2.0 Ga rocks therefore appear to constitute part of the Transamazonian craton. The reentrant in the craton at the bight in the present-day continental margin may therefore be a feature dating back to its inception during late Precambrian to earliest Paleozoic rifting (see Dewey and Lamb, 1992).

Juxtaposition of the Atlantic margin of the Laurentian craton with the Pacific margin of the South American craton using the PLATES software of the Institute for Geophysics of the University of Texas at Austin shows that the Labrador-Greenland promontory is the correct size and shape to have rifted from the Arica reentrant (Fig. 1). Moreover, the reconstruction indicates that the Arequipa massif could be explained as a segment of the Makkovik-Ketilidian province of Labrador and southern Greenland (Hoffman, 1989; Gower et al., 1990). The Grenville province of Laurentia could have continued beneath the ensialic Andean Cordillera of the present day to join up with the 1.3-1.0 Ga San Ignacio and Sonsas-Aguapei orogens that border the Transamazonian cratonic nucleus (Litherland et al., 1985; Teixeira et al., 1989). These in turn could have been continuous with the Sveco-Norwegian province of Baltica (Fig. 2). Precambrian rocks have been found at two localities within the Andean Cordillera immediately to the east of the Arequipa massif. Rocks from the Belén massif of northernmost Chile, and from a borehole in the Bolivian Altiplano, have yielded ages of ca. 1.0 Ga (Lehmann, 1978; Pacci et al., 1981). Despite uncertainty regarding the significance of the result from the Belén rocks, a broadly "Grenvillian" age seems likely (Baeza and Pichowiak, 1988). Thus a candidate for the continuation of the Grenville front can be located within the Arica reentrant opposite the equivalent piercing point on the Labrador-Greenland promontory of Laurentia (Fig. 1).

IMPLICATIONS

The geometric and geologic match of the Atlantic margin of Laurentian craton and the Pacific margin of the South American craton, constitutes additional evidence in support of the hypothesis that Laurentia originated between East Gondwana and the several cratons of West Gondwana (Moores, 1991; Dalziel, 1991, 1992; Hoffman, 1991). Thus, an early Neoproterozoic supercontinent (Fig. 2), assembled during the 1.3-1.0 Ga Grenvillian interval, may have included the Amazonian, West African, and Rio de la Plata cratons as well as Laurentia, Siberia, Baltica, East Gondwana, the Kalahari craton, and (possibly) the Congo-São Francisco craton.

As mentioned above, time and space considerations suggest that the Transantarctic-eastern Australian margin separated from Laurentia to open the Pacific Ocean basin at the time the Windermere passive margin developed during the mid-Neoproterozoic (Ross, 1991; Dalziel, 1992; Hoffman, 1992). However, stratigraphic data from western Newfoundland (Williams and Hiscott, 1987) indicate that, despite evidence of rifting along the Appalachian margin of the Laurentian craton at about that time (Hatcher et al., 1989), the rift-drift transition did not take place there until the earliest

Cambrian (ca. 540 Ma; Compston et al., 1992) when thermal subsidence began (Bond et al., 1984; Bond and Kominz, 1991). As Gondwana appears to have amalgamated by about 600 Ma (see Dalziel, 1992 for discussion), a further implication of the proposed fit of the Labrador-Greenland promontory and the Arica reentrant is that Laurentia and Gondwana formed part of a different supercontinent in the late Neoproterozoic after the opening of the Pacific Ocean basin (Fig. 3).

This possibility needs to be taken into account in considering the environmental changes that took place at the end of the Precambrian, and the emergence of multicellular organisms. The paleomagnetic poles from Laurentian rocks used to position the supercontinents in the reconstructions for 750 and 570 Ma (Figs. 2 and 3) are in keeping with the suggestion of Park (1992) that Laurentia may have moved across the South Pole near the Precambrian-Cambrian boundary. Two supercontinental assemblies during the Neoproterozoic in approximately the paleolatitudes shown, separated by the opening of the Pacific Ocean basin and the amalgamation of Gondwana, may help to explain the time-space distribution of glacial deposits formed during that interval (Chumakov and Elston, 1989). The hypothesis of a regular "supercontinental cycle" (Murphy and Nance, 1992; Turcotte and Kay, 1992; Hartnady, 1993), is called into question by the reconstructions, especially as Laurentia broke away from the late Neoproterozoic supercontinent soon after it had formed, and seems to have reunited with Gondwana three times, during its Paleozoic journey around the proto-Andean margin of Gondwana (Dalla Salda et al., 1992a, 1992b; Dalziel et al., 1992). Amalgamation of several cratons to form supercontinents from time to time seems inevitable on the surface of a dynamic earth of constant radius (Duncan et al., 1992).

A further implication of the proposed fit is that, despite significant modification of their margins as a result of Phanerozoic tectonism, the discrete cratons that separated during the Neoproterozoic were very robust entities indeed. For example, if the Labrador-Greenland promontory and the Arica reentrant are related as suggested here, the present-day Arica bight originated in a latest Neoproterozoic to earliest Paleozoic rift event (see Dewey and Lamb, 1992). Knowledge of the growth of the South Atlantic Ocean basin precludes major modification of the eastern margin of South America during the Mesozoic and Cenozoic. Paleomagnetic data suggest movement of small blocks along the Pacific margin into the Arica bight during the Mesozoic and Cenozoic (Beck, 1988), but there are no data to suggest that the bend in the Andean Cordillera there is secondary. Thus the basic shape of the bight may be inherited from rifting of the Labrador-Greenland promontory of Laurentia from the Arica reentrant of Gondwana at a triple junction with a failed arm that formed the Paleozoic ensialic orogen between the Arequipa massif and the cratonic nucleus of Amazonia (Fig. 1; Dalmayrac et al., 1980). In that case the Altiplano may owe its existence to that ancient extensional event and to the consequent modification of Phanerozoic tectonic processes by the presence of the reentrant (Isacks, 1988; Scanlan and Turner, 1992).

Paleomagnetic data are compatible with clockwise rotation of Laurentia around the Pacific margin of Gondwana during the Paleozoic *en route* to final "docking" with northwestern Africa (present coordinates) to form Pangea (Dalziel, 1991, Fig. 2). Indeed several lines of evidence suggest that, following initial separation in the latest Neoproterozoic to Early Cambrian, Laurentia may have tectonically interacted with the Pacific margin of South America in the course of this motion (Dalla Salda et al., 1992a,b; Dalziel et al., 1992 and in press). The accompanying figure shows hypothetical, but paleomagnetically acceptable, relations of Laurentia and South America at specific times from the end of the Precambrian to the assembly of Pangea in the latest Paleozoic. The reconstructions may explain several long-standing tectonic problems, yet they do not appear to conflict with well-established interaction between Laurentia, Baltica, and other tectonic units of the present-day North Atlantic region. Critical elements of the overall hypothesis are outlined below. The suggestion of specific times of continent–continent collision is not meant to imply simple tectonic settings. The zone between the continents would have been as complex as the Tethys or present-day Mediterranean.

Latest Precambrian (570 Ma): The Labrador-Greenland promontory of Laurentia rifts from the Arica reentrant in the Gondwana margin,

possibly while some Brazilide basins are still closing. The Arequipa massif is a fragment of the Ketilidian-Makkovik provinces of Greenland and Labrador. The Paleozoic intracratonic basin between the Arequipa and the Amazonian shield may mark a failed arm of the rift system.

Cambrian-Early Ordovician (500 Ma): Laurentia rifts from the proto-Andean margin, isolating the benthic trilobite fauna of the continent. The "southern cone" (from Georgia in the east to Trans-Pecos Texas in the west) may have remained attached to Gondwana in the vicinity of the present-day Weddell Sea.

Mid-Ordovician (487 Ma): Laurentia and Gondwana collide to form the Taconic-Famatinian (Ocloyic) orogen, possibly continuing into the Shackleton Range of Antarctica. Upon subsequent rifting (possibly pre-Ashgillian), the Precordilleran terrane of northwestern Argentina is detached from the Ouachita embayment of Laurentia, and the Oaxaca terrane of Mexico is detached from the area of the Arica reentrant of South America.

Late Ordovician and Silurian (422 Ma): Laurentia and Gondwana separate. Laurentia occupies temperate to tropical latitudes while the Pacific margin of Gondwana undergoes glaciation.

Devonian (374 Ma): Following the Laurentia-Baltica collision that ended the Caledonian orogeny, Laurentia and Gondwana collide once again in a dominantly right-lateral transpressive mode. Much of what is known as the Acadian orogeny in North America may reflect this interaction. Distribution of the Malvinokaffric and Cosmopolitan faunas would have been strongly influenced by the changing paleogeography over this time interval. Subduction of Pacific Ocean floor commences beneath the central Chilean margin.

Latest Paleozoic (265 Ma): Laurentia finally docks with present-day northwestern Africa in the Ouachita-Alleghanian orogenesis to terminate the Appalachian revolution and complete the amalgamation of Pangea. Pacific Ocean floor is subducted beneath the entire proto-Andean margin.

The hypothesis, if basically correct, has several major implications for the development of the Andean Cordillera in the Mesozoic and Cenozoic. For example: 1. As suggested by others (e.g., Dewey and Lamb, 1992) from a purely South American standpoint, the Arica reentrant may be an original feature and may have exerted control over the tectonic development of the Pacific margin throughout the Phanerozoic. The Patagonian and Colombian oroclines may also date from initial rifting. 2. The crust beneath the Altiplano may have been thickened initially in Grenvillian collision of the Laurentian craton with Amazonia. 3. Laurentia may have played a critical role in the diachronous initiation of subduction of Pacific Ocean floor beneath South America. 4. Subduction erosion along the Pacific margin of South America may have been limited to material accreted during the Phanerozoic.

CONCLUSIONS

These geologic correlations between Precambrian rocks of Laurentia and East Antarctica-Australia and South America have led to a new and testable scenario for the opening of the Pacific Ocean basin and the amalgamation of Gondwana. This is turn allows a fresh look to be taken at the so-called supercontinental cycle over the past 1 billion years. Rodinia, the supercontinent formed during Grenvillian orogenesis appears to have existed for approximately 250 my, while another supercontinent, as yet unnamed, may have existed fleetingly towards the end of Precambrian times. The suggestion that Laurentia then collided with the proto-Andean margin of South America in mid-Ordovician and again in Devonian times, leads to the possibility that two Laurentia-Gondwana "supercontinents" were formed and then fragmented during the Paleozoic era prior to the amalgamation of Pangea in the Ouachita-Alleghenian orogeny. These events appear to be more like the chance encounters of continental masses moving on a dynamic earth of constant radius than the reflection of a tectonic "cycle."

The concept of global orogenies, Umgrove's "pulse of the earth", has fallen into disfavor since the advent of plate tectonics in the 1960's and 1970's. However, the suggested Laurentia-Gondwana collisions during

early and mid-Paleozoic times, like the Ouachita-Alleghenian event at the end of the Paleozoic Era, correlate with major sequence boundaries in cratonic interiors. There may, therefore, be more to old ideas regarding close interaction between global tectonic and environmental changes than has recently been acknowledged.

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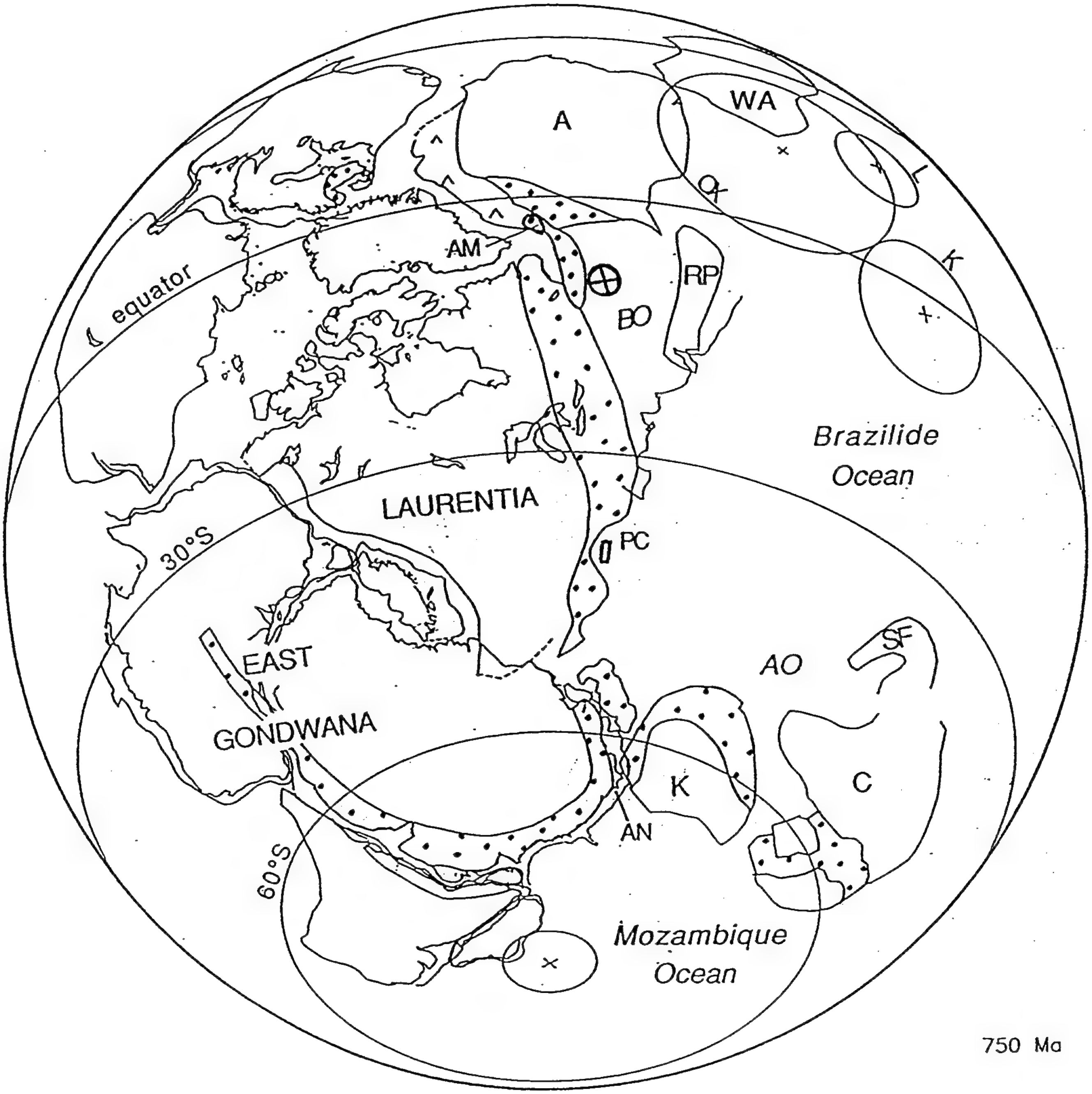

Figure 1. Geologically-controlled reconstruction of a Neoproterozoic supercontinent for the period ca. 1.0 - 0.75 Ga (Dalziel, 1992b, figure 2). The south pole is shown relative to Laurentia based on the McKenzie Mountains pole of Park et al. (1989) for ca. 0.75 Ga, the small circle about the pole is the alpha 95 circle of confidence.

The circle with inscribed cross represents the hypothetical position of the Oaxaca terrane within Gondwana prior to the mid-Ordovician as described in the text. The rectangle marked PC represents the hypothetical position of the Precordilleran terrane (part of the larger Occidentalia terrane of Dalla Salda et al., 1992a) within the Ouachita embayment prior to the mid-Ordovician as suggested by Dalla Salda et al. (1992b) and described in the text. The small circles labelled L (Laurentia), OX (Oaxaca), K (Kalahari) are the alpha 95 circles of confidence about the mean poles for ca. 0.95 Ga described in the text. Grenvillian belts (ca. 1.3-1.0 Ga) are stippled

AM - Arequipa massif; AN - Annandagstoppane; AO - Adomaster Ocean; A - Amazonia; BO - "Brazilide" Ocean; C - Congo craton; RP - Rio Plata craton; SF - Sao Francisco craton; WA - West African craton

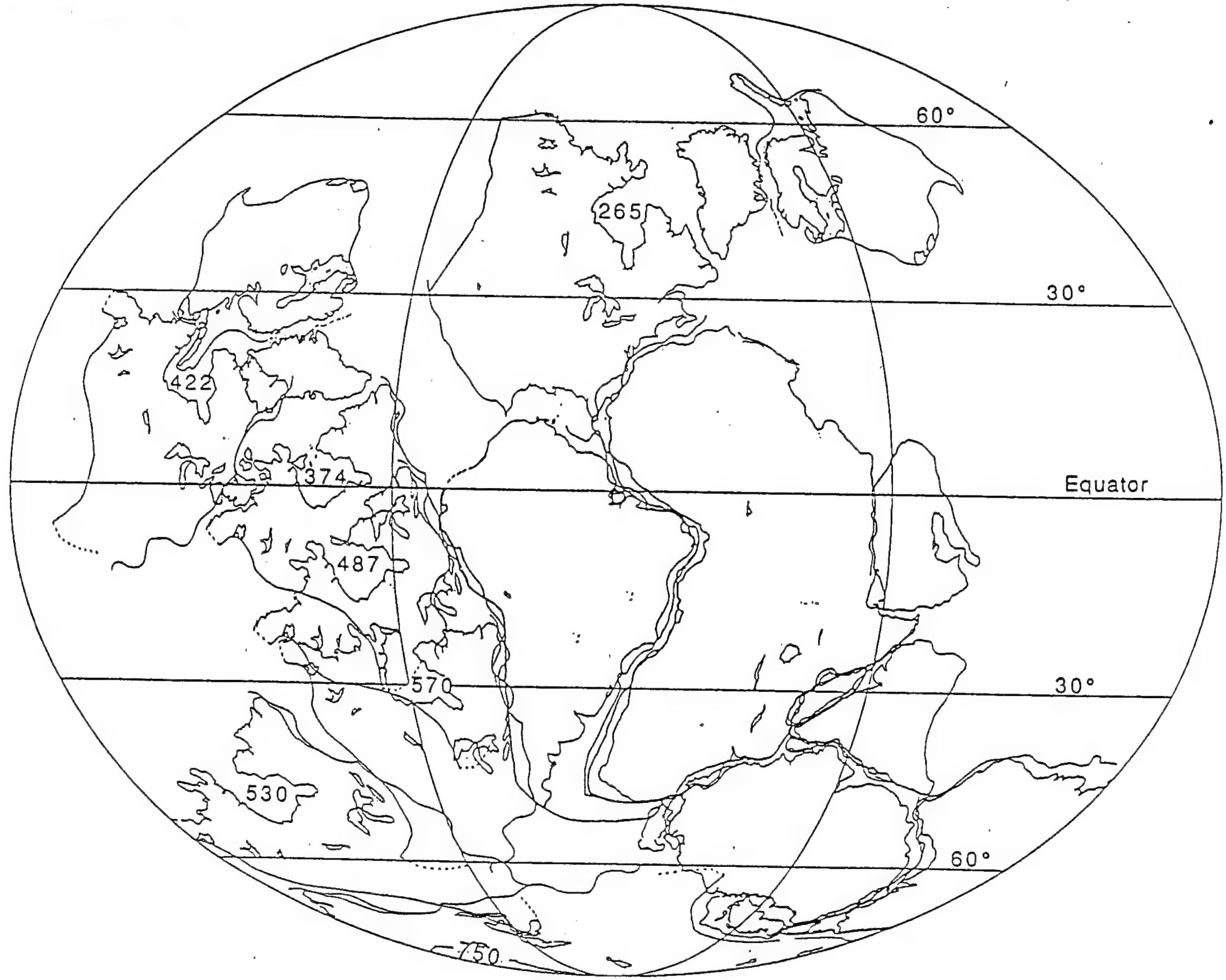

Figure 2. Molleweide projection showing hypothetical, but paleomagnetically acceptable, positions of Laurentia with respect to South America during the Paleozoic. The figure is modified from an earlier diagram (Dalziel, 1991, Figure 2) that was constructed to show that Laurentia could have "broken out" from between East Antarctica-Australia and South America at the end of the Precambrian. In the present figure, Gondwana is reconstructed using marine geophysical data as before, with South America kept in its present-day coordinates. Paleomagnetic controls are mainly from Van Der Voo (1988).

Early Neoproterozoic Laurentia (ca. 750 Ma) is shown against East Antarctica-Australia as it may have been prior to opening of the Pacific Ocean basin and amalgamation of Gondwana (Moores, 1991; Dalziel 1991; Hoffman, 1991). Laurentia is shown in the late Neoproterozoic (ca. 570 Ma) with the Labrador-Greenland promontory located within the Arica reentrant (Dalziel, 1992b). The position for the Early Ordovician (500 Ma) is as in Dalziel (1991 and 1992a). The Laurentia-Gondwana collision suggested by Dalla Salda (1992a, b) to have resulted in the Taconic-Famatinian (-Shackleton?) orogen is shown at 487 Ma; this is perhaps about 25 million years too early for the main deformation and metamorphism, but the paleomagnetic control is better. The position for Laurentia at 422 Ma is that of Dalziel (1991). Right-lateral transpression between Laurentia and Gondwana suggested to account for the main effects of the Acadian orogeny is indicated at 374 Ma (Dalziel et al., 1992 and in press); this is rather late for the Acadian, but again the paleomagnetic control is better. The reconstruction of Pangea by ca. 265 Ma is based on marine geophysical data.

Investigations of Convergent Margins Using Three-Dimensional Seismic Reflection Imaging Techniques

Thomas H. Shipley, Institute for Geophysics, The University of Texas at Austin

ABSTRACT

Structural evolution and fluids are inextricably linked in convergent margin accretionary prisms. While the basic geometry of accretionary prisms is well documented, the internal structure that relates to tectonic processes is only imaged in a few exceptional cases. Thus the basic structural evolution in accretionary prisms is poorly known. To help resolve some of these issues we adapted conventional three-dimensional (3-D) seismic imaging techniques to this problem. We have recorded 3-D seismic reflection data sets from two accretionary prisms, Costa Rica and Barbados, which share processes common to mud-dominated trench systems.

The Costa Rica 9 × 23 km data set was collected in 1987 along the Middle America Trench off the Nicoya Peninsula. Massive dewatering of the underthrust section is postulated within a few kilometers of the trench. Mud volcanoes and diapirs are common. Bright-spot fluid accumulations, including minor gas, occur at the slope cover-accretionary prism contact. Major through-going out-of-sequence faults apparently produce efficient paths for migration of fluids from deep levels of the prism to the lower slope. There is good evidence for forearc extension coeval with frontal accretion and underplating.

The Barbados 5 × 25 km data set was collected in 1992 over a portion of the lower slope examined in three DSDP/ODP drilling programs. The décollement is usually a compound negative-polarity reflection modeled as a low-velocity, high-porosity zone less than ~14 m thick. The seismically defined fault is inferred to be a thin, high-porosity zone and is thus an undercompacted, high-fluid-pressure dilatant section. Map-view variations in seismic-reflection waveform and amplitude illustrate complex patterns of fault-zone fluid content and fluid pressure. Several areas of positive-polarity fault reflections define square kilometer-sized regions inferred to be lower porosity sections producing strong asperities in an otherwise weak fault. ODP Leg 156 drilling in this area in June and July 1994 discovered fluid pressures in the décollement at near lithostatic values and abnormally high porosities.

INTRODUCTION

Twenty years ago, the predecessor institution of UTIG collected the first multichannel seismic data by an academic institution. This was milestone for the institution and for future academic marine geophysical work. Seven years ago, UTIG collected a three-dimensional seismic reflection data set off Costa Rica, again the first academic institution to do so. These data were then processed using the UT Supercomputer facility and commercial software. This was a second milestone in offshore marine geophysics because it provided new images and perspectives within structurally complex areas. In a period of seven years we have collected novel 3-D data sets off Costa Rica, New Jersey and Barbados.

After working in the structurally complex regions with conventional seismic reflection data the imaging limitations began to be recognized as severe (e.g., Coltrin et al., 1989). A seismic line offshore the Middle America Trench was interpreted by two groups of scientists which published their line drawings of the identical section. These are reproduced in Figure 1 which illustrate the degree to which even the fundamental geometry of reflecting horizons is so poorly imaged that the interpretations are unconstrained by the observational data. It was this sort of problem that lead to our first 3-D survey. It was expected that the 3-D technique would improve reflection continuity by more adequately correcting for out-of-plane reflections. The extent of this improvement, given the water depths and structural scales involved is not the

entire solution to the problem but has shown itself to be a very important step.

The Costa Rica and Barbados surveys reviewed here were designed in part to investigate aspects of the processes involved in accretion and subduction at the base of trench slopes. Many models of active margins have been proposed from examination of mountain belts and have then been applied to modern margin settings and used to guide interpretations of seismic cross sections (e.g., Boyer and Elliott, 1992). The only direct information in internal structure comes from seismic reflection studies across many submerged margins. Some seismic data show exceptionally well defined structures such as Nankai (e.g., Aoki et al., 1982) and Barbados (e.g., Westbrook and Smith, 1983). However, few of the even most revealing seismic data show detail more than 10 km arcward of the trench axis.

Another area where 3-D techniques have proven useful is in the examination of fault properties. Abnormal pore-fluid pressures cause a large reduction in rock strength and thus has profound effects on fault mechanics (e.g., Hubbert and Rubey, 1959). Coulomb models of the accretionary prism being near failure requires high fluid pressures within the prism and along the basal detachment (décollement) (Davis et al., 1983; Dahlen, 1990). However, there are no direct observations of elevated fluid pressures within modern, active prisms. Mapping of fault plane reflections and their waveform variations in 3-D offer new insights into fault-controlled fluid flow.

SUMMARY FOR COSTA RICA

The top of the oceanic basement is well-defined seismically from the trench to the shelf edge (Figs. 1 and 2). Reflection profiles show that all of the oceanic pelagic sediments are underthrust beneath the toe of slope, with some of the overlying hemipelagic section scraped off in front of the prism and accreted to it. The shallow zone of offscraping is partly responsible for the nearly reflection-free sediment wedge right at the base of the slope (Fig. 2). The small amount of offscraping and the frontal accretion suggest that much of the growth of the prism must be by underplating, that is, by the transfer of material from the underthrust section to the bottom of the prism. From 25 km arcward of the trench to the shelf edge a zone of reflections 500 m to 100 m thick exist just above the downgoing slab, then ramp upwards at 20 to 30 km from the trench. The upper extent of these ramps are often associated with small offsets at the top of the prism, suggesting they are active faults. The top of the prism produces a distinctive high-amplitude reflection which has been highly disrupted and offset.

The detailed interpretation of this data set is continuing (Stoffa, et al., 1991; Shipley et al., 1992; McIntosh et al., 1993). The structural diversity at all scales shows how important the 3-D data volume is to interpretation. Much of the diversity appears to be tied to the irregular basement topography. In summary sediments are actively being added to the front of the prism, but at the same time only a few kilometers arcward, the prism is continuing to thicken and grow. The two identified processes are the addition of underthrust oceanic section in fault-bounded blocks (duplexes) at the base of the wedge, and by prism-wide young faults that dissect the wedge and produce the most convincing seismic reflections of through-going structures. These later faults are usually referred to as out-of-sequence since they are not part of a sequential fault stack.

The duplex and out-of-sequence faults occur in close proximity to the trench axis and thus these processes occur very early in the deformation history of modern prisms. Therefore, adjustments to maintain critical taper begin very early in the accretion process and must be fairly continuous, and may also help explain the complexity of structure in the very young accreted section. At the larger scale, the previously unrecognized intraprism faults impart a well-defined structural architecture that potentially controls prism-wide fluid flow pathways.

SUMMARY FOR BARBADOS

Given the well-determined evidence of fluid flow and the extensive Deep Sea Drilling Project (DSDP) and ODP data, we conducted the Barbados survey to examine the seismic characteristics of the décollement fault-plane reflection in three dimensions (Shipley et al., 1994). An east trending seismic line that crosses through Site 671B illustrates the main

structural features of the toe region (Fig. 3). These data are consistent with earlier data and interpretations that show an extraordinary fault reflection observed to at least 70 km west of the trench (e.g., Westbrook and Smith, 1983). The semitransparent zone in the prism 5 to 8 km from the thrust front is a feature common to this prism and to the north (Bangs and Westbrook, 1991) (Fig. 3). Progressive rotation and multiple deformation paths create structures undetectable at seismic scales.

In the three-dimensional surveyed area, the fault-reflection polarity is nearly 180° shifted in phase as referenced to the sea floor. Normal-polarity regions are rare but easily mapped. The preliminary waveform analysis shows that the décollement is a compound reflection from a thin layer. A map of the peak amplitude associated with either the negative part of the compound reflection or the peak of the positive-polarity reflection is shown in Figure 4. It illustrates that across most of the area the fault reflection is weakly negative with the largest negative amplitudes aligning along an east-northeast-trending band <2 km wide. Structural contours of the fault surface do not indicate any relationship to the amplitude pattern from structural closure on the fault surface.

The fault plane waveform and amplitude apparently illustrate a complicated pattern of fluid content. Relatively high fluid content (and porosity) implies undercompaction and relatively high fluid pressures. High fluid pressures produce low shear strength. Most of the fault must be weak within a few tens of kilometres of the trench which is consistent with the low wedge taper. A few areas of positive polarity suggest localized zones where fluid content of the fault decreases normally with depth and thus the fault has no unusual pore-fluid pressures. These should then be stronger regions of the fault surface and should produce a noticeable change in the local stress pattern.

The negative-polarity sections are dilatant zones within the fault. Because permeability is strongly correlated with porosity, the dilatant zones may be locations of channelized fluid flow (Shipley et al., 1994). If these dilatant zones represent hydrofractures, they must either be young or remain open due to constant fluid replenishment from depth. Thus, the map may be an image of both fault strength and potential fluid conduits. The confirmation or rejection of these speculations awaits results of permeability measurements and long-term fluid-pressure monitoring of this fault from ODP Leg 156 (Shipboard Sci. Party, 1994).

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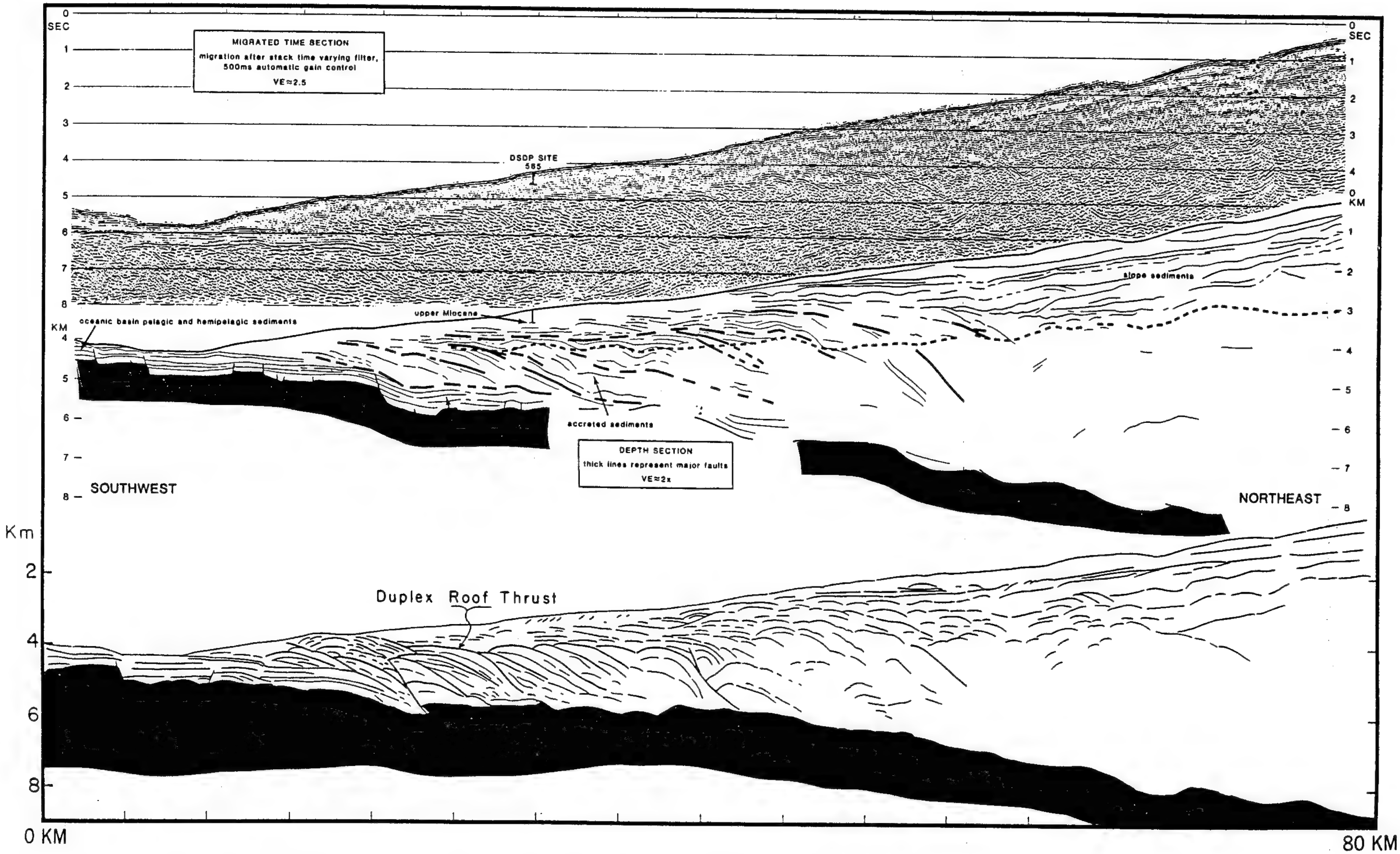

Figure 1. Two interpretations of UTIG line 7 from the Middle America Trench off Costa Rica. The top interpretation was made by Shipley and Buffler (1987), the bottom by Silver et al. (1985). The landward dips of the primary reflecting horizons within the accreted section are very different in the two line-drawings.

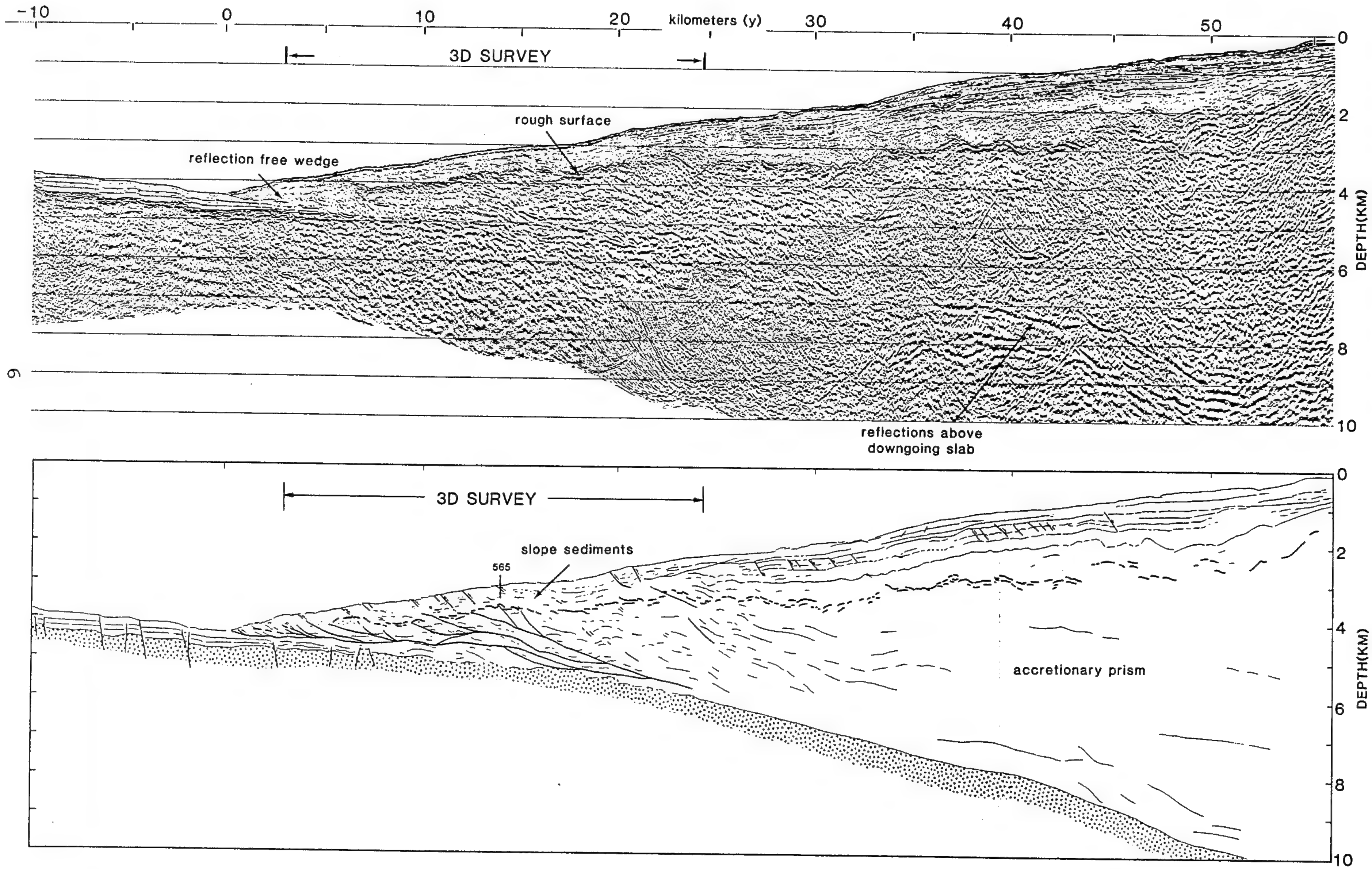

Figure 2. This section shows the newer data and interpretation incorporating the 3-D survey results (after Shipley et al., 1992). Compare with Figure 1.

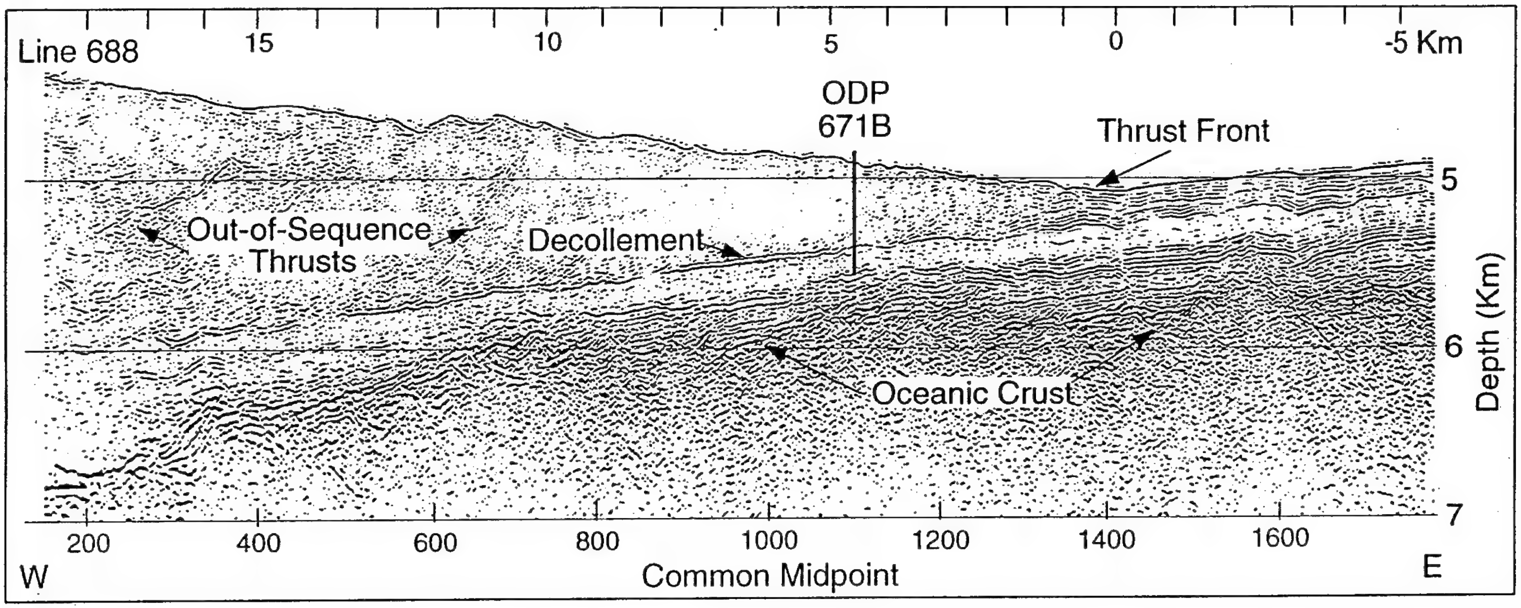

Figure 3. Section of east-west seismic Line 688 (passing through Ocean Drilling Project (ODP) Site 671B). The décollement reflection is separated by reflection-free intervals above and below, simplifying its study. Out-of-sequence thrusts are identified seismically 10 km west of the thrust front (after Shipley et al., 1994)

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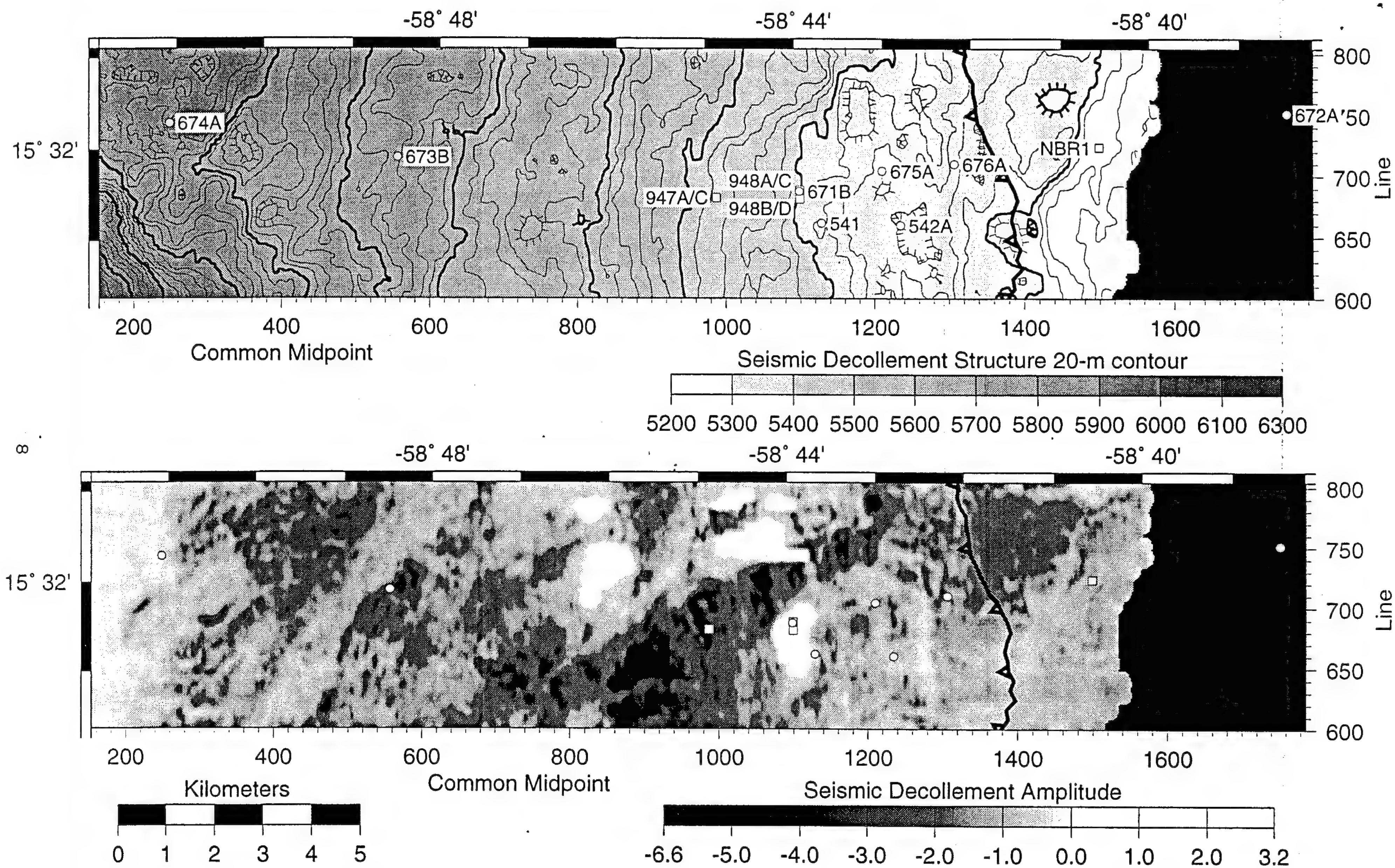

Figure 4. Top is map showing the structure of the décollement fault surface. Bottom is map of décollement created by digitizing the seismic amplitude along all 204 3-D lines. Mapped east of thrust front is incipient fault identified at Site 672A (after Shipley et al. 1994).

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Melt Delivery at Mid-Ocean Ridges

Jan D. Garmany, Institute for Geophysics, The University of Texas at Austin

INTRODUCTION

In April and May 1993, we conducted an OBS survey of the East Pacific Rise (EPR) to test the hypotheses that melt is delivered to the mid-ocean ridge system episodically and over a region much wider than the observed neovolcanic zone. The primary goal of this survey was to determine the frequency of occurrence of melt at or near the base of the crust. From previous seismic observations and modelling, we argued that the detection of intense, high phase velocity converted shear waves would be strong evidence for the presence of melt. The experimental geometry was chosen to maximize the probability of seeing such converted phases. Using an objective criterion for the detection of these phases, we determined that the areal coverage of the Moho by melt between 10 and 30 km from the ridge axis was approximately 10%. This amount is broadly consistent with a wide zone of melt delivery, based on simple thermal and statistical arguments and using a model of random sill emplacement for the delivery of melt. The best estimate for the maximum thickness of the sills is 300 meters of intruded basalt, possibly increased by the addition of ultramafic materials. This figure is completely consistent with observations of intrusions in ophiolite complexes.

OBSERVATIONS OF P-TO-S CONVERSIONS FROM NEAR THE MOHO (PmS)

While observations of P-to-S conversions upon reflection at the Moho (a phase denoted PmS) predate this work, we have produced many more observations of excellent quality as a result of our survey. Observations of PmS were previously rare because standard seismic data acquisition geometries discriminate strongly against its detection. We show a particularly beautiful example of the phase in Fig. 1, and the presence of this phase is diagnostic of anomalous Moho. The phase is a strikingly intense shear wave occurring around 1 second behind the P wave and having nearly the same phase velocity as P. While PmS is visible in the normal Moho case, it is quite weak. If the Moho is at all gradational, the PmS phase disappears almost completely. The very low rigidity of the thin layer at the Moho is necessary to get the high amplitude shear wave in the synthetics. We infer that there must be a low rigidity body, presumably a melt filled sill, at the Moho if PmS is clearly observed.

GEOMETRY OF PmS RAYS AND EXPERIMENTAL GEOMETRY

By Snell's Law, the angle of reflection of a converted shear wave from the Moho is steeper than the angle of incidence of the compressional wave. Because of this, the point of reflection is always rather close to the receiver. The restrictive geometry of the ray permits a simple interpretation of the delay of the shear wave after the P wave. Since the conversions must occur on a cone with its vertex at the receiver (roughly), the delay may be used to estimate the depth at which the reflection occurred and also the horizontal distance away from the receiver. For a constant depth to the level of reflection, the points of reflection on the Moho describe nearly circular arcs when the seismic sources are on lines that are offset from the receivers, greatly increasing the sampling of the Moho (Fig. 2). As the point of reflection moves over the Moho, the PmS phase appears intermittently in the off-line seismic data, giving a direct estimate of the sizes of the anomalous Moho regions. They are on the order of a few to several km in diameter.

The determination of the presence and absence of PmS is done by correlation of vertical and horizontal data. These correlation functions are used with the simple geometry of the PmS ray system to generate a plan view of PmS reflectivity directly. We show the top 8.5% of the estimator values in dark overlayed on a picture of the seafloor topography (Fig. 3).

CONCLUSIONS

A statistical model for the cooling of randomly produced melt sills gives us a simple formula for the expected areal coverage of the Moho by melt. This model tells us that the areal coverage is proportional to the maximum (or else the expected) thickness of the intrusions. The constant of proportionality is fairly well known and depends on the spreading rate and on the thermal properties and conditions near the Moho. We obtain an estimate of 300 m for the maximum thickness of intrusions beneath the crust by considering our observations and the thermal model. This thickness is geologically reasonable, and it is consistent with the likely thermal structure and basalt budget by construction. Independent observations indicate that some intrusions may be much larger, and indeed the widespread occurrence of seamounts testifies to strongly episodic melt delivery from time to time. However, the primary consequence of this work is that episodic delivery of relatively large amounts of basalt (~ 1 km^3) is a common event, and that probably most of the basaltic material in the crust is delivered in this manner. The consequences of this model for the detailed structure of the ridge axis are still a matter of conjecture. If the ridge low velocity region is primarily mafic, then melt intruded at the base of the crust may be quite mobile, and anatexis (remelting of crustal rocks) is probably quite important. If there is an ultramafic component in the central low velocity region, it must be quite dilute (~40%) in order not to contradict seismic and gravity constraints. We look forward to further studies of these results.

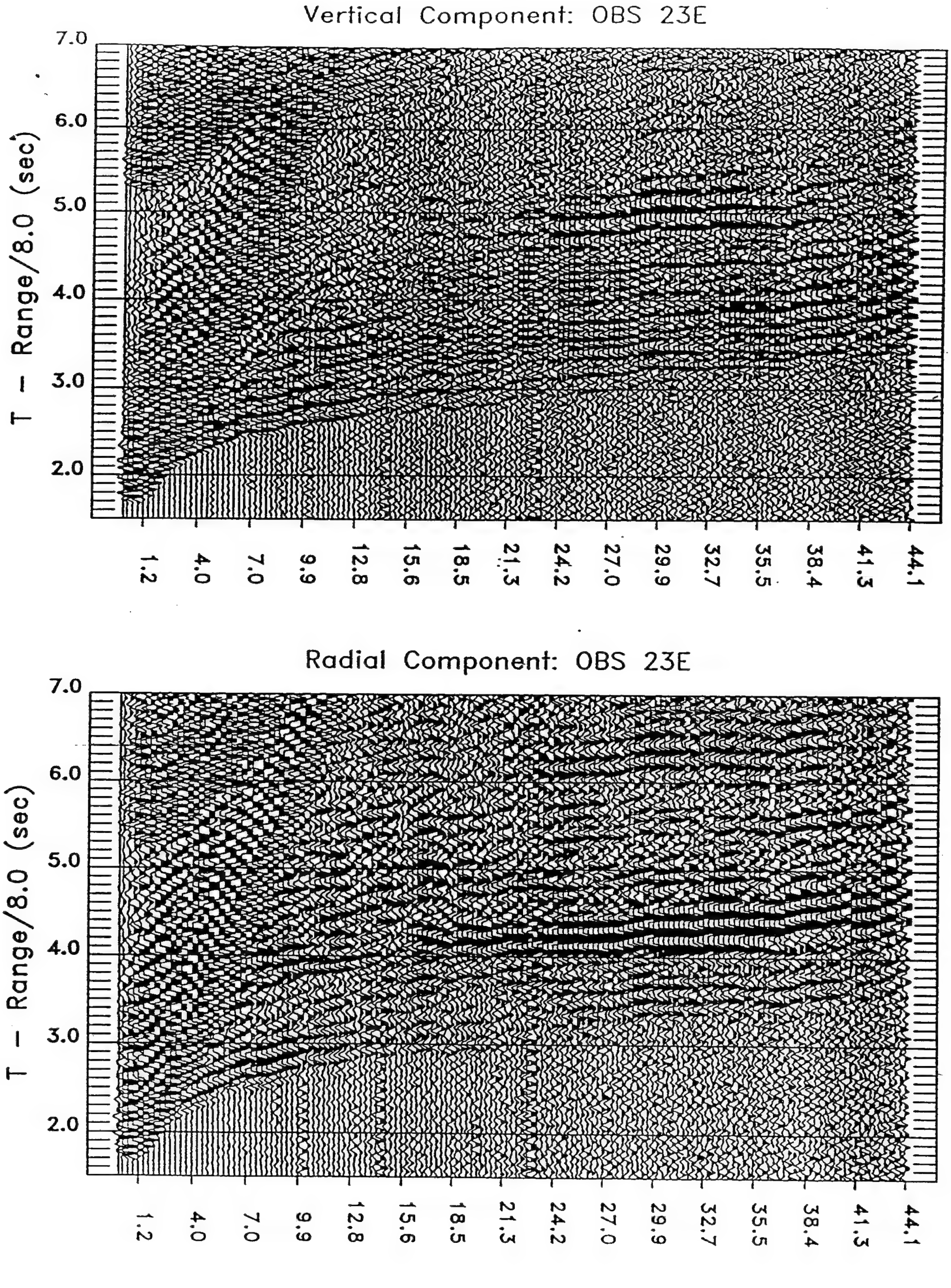


Figure 1. Displays of vertical and radial (horizontal) motion as functions of distance and time. Radial component panel shows intense PmS phase near 4 seconds time (reduced) from 16 km range to the end of the section. This phase is not apparent on the vertical component panel, indicating horizontal polarization characteristic of shear waves.

Experimental Geometry

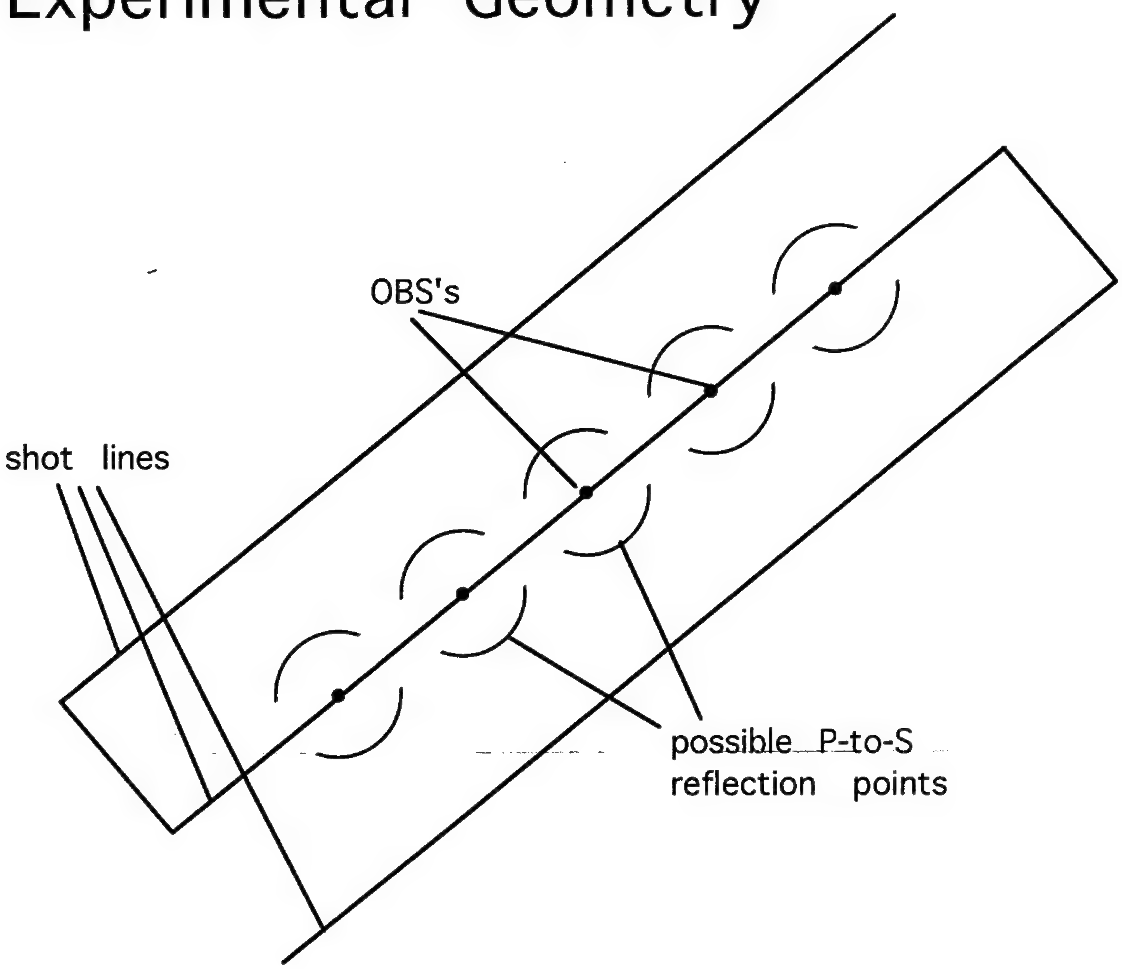
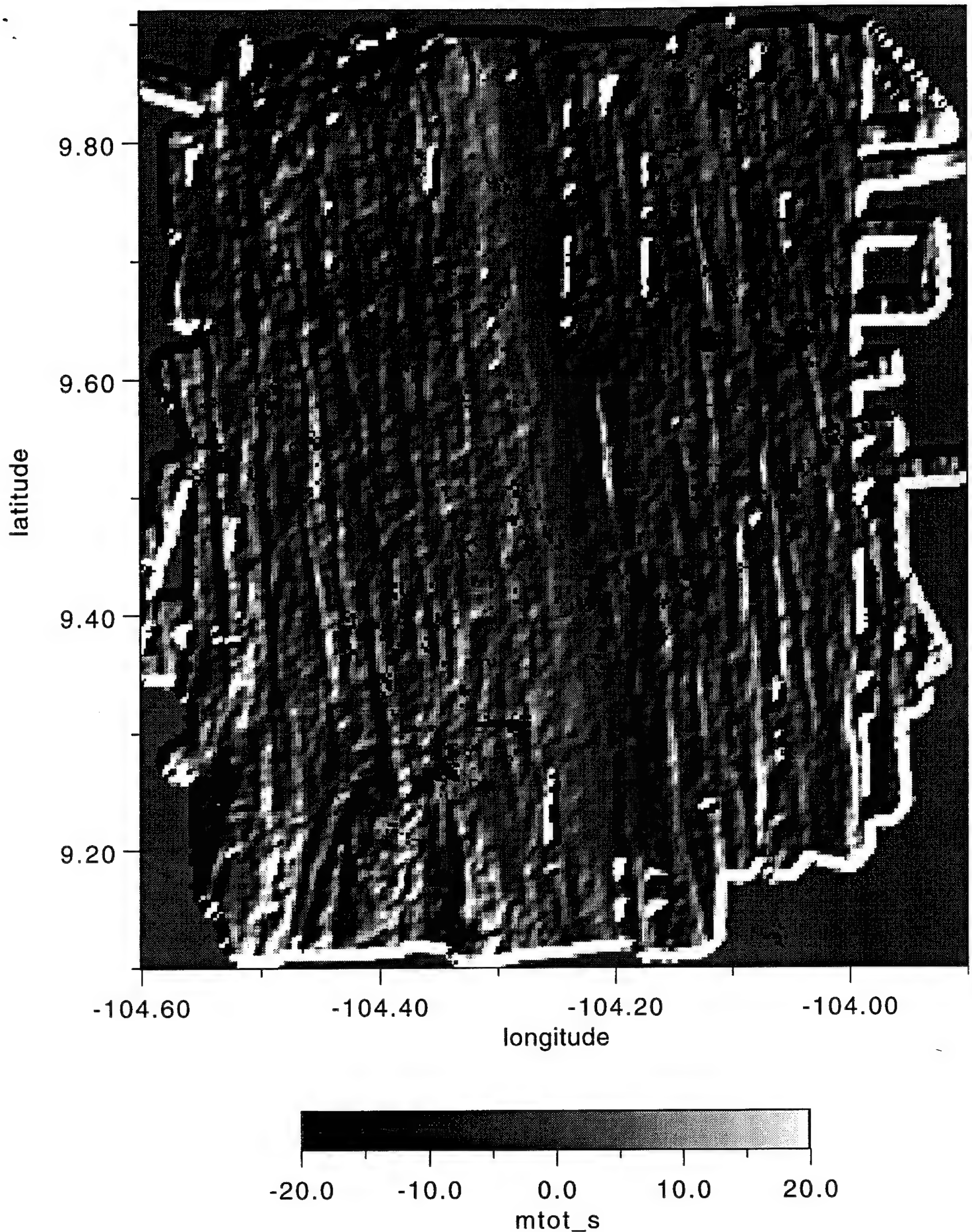


Figure 2. Geometry of experiment is chosen to increase number of points where P-to-S reflectivity is sampled by using off-line shots to OBS array. Results of survey show striking variations in reflectivity as seen by single receivers.

Figure 3. Melt (dark) overplotted on bathymetry



combo vs. (row, col)

THE EARLIEST ATTEMPTS TO MEASURE HEAT FLOW THROUGH THE DEEP SEA FLOOR

Hans Petterson was the inspiring and foresighted leader of the *Swedish Deep Sea Expedition 1947-48.* In his plans for the research program of the expedition, he gave high priority to measurements of the geothermal gradient in the deep sea floor, a novel experiment. Besides the obvious interest in the question of heat loss by the Earth through a region that represented more than half of its surface area, Hans Petterson was particularly interested in the thermal contribution from radioactive decay by the uranium and thorium series elements, which he had shown earlier to be highly enriched in the slowly depositing deep sea sediments. The question of the total thickness of the ocean sediments, and the nature of the deep basement rocks, was also looming large in geophysics in the 30s and 40s.

The expedition was mainly devoted to exploration of the deep sea floor, using the revolutionary piston corer developed by Börje Kullenberg, in conjunction with Weibull's seismic reflection technique. Other systematic studies were carried out in physical, chemical and biological oceanography during the voyage, which lasted for 15 months, circumnavigating the globe in the low latitudes.

Several factors contributed to limiting the number of measurements of sediment temperature gradient that could actually be carried out. The up to 15 m long thermometer probe had to stay inserted in the tough sediment for about 45 minutes for adequate thermal equilibration to be achieved. This undesirably effective anchorage posed a threat to the wire rope, when the probe had to be pulled out. Another serious setback was the repeated malfunctioning of the clockwork and the valves of the liquid thermometer columns, when chilled to the near-zero temperature of the bottom water.

As a result, out of several attempts, only three reliable measurements were obtained, all in the central equatorial Pacific—they consistently gave temperature gradients that exceeded previous predictions. The surprisingly high heat-flow values derived from these measurements suggested to Petterson a need for re-evaluation of the generation and transport of heat in the outer layers of the Earth, and he regretted the loss of opportunity to pursue these initial measurements further.

It was fortunate for geophysics that Art Maxwell's successful attempts, undertaken with more sophisticated electronic equipment during the *Capricorn Expedition,* could explain and vastly expand these unexpected results, and contribute to the great plate tectonics revolution that was to follow.

Gustaf Arrhenius
Scripps Institution of Oceanography

AGENDA

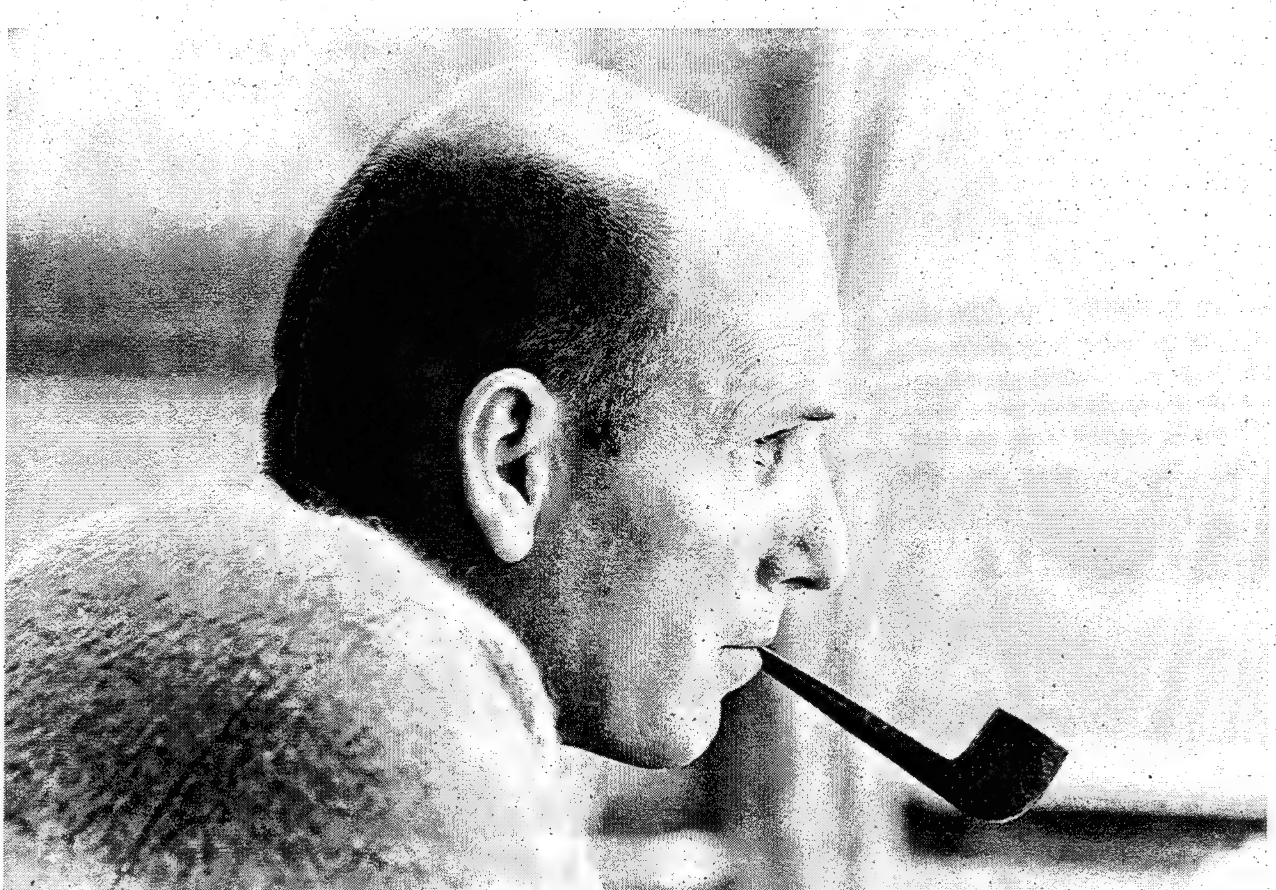
WEDNESDAY

SEPTEMBER 28, 1994
LILA B. ETTER ALUMNI CENTER, GRAND BALLROOM
PRESIDING—JOHN G. SCLATER, SIO

2:00	Welcome *Paul L. Stoffa*
	Early heat flow measurements during the Swedish Deep Sea Expedition 1947-1948 *Gustaf Arrhenius, SIO • 2:10—2:30*
	Marine geothermal research and ocean drilling (DSDP Leg 3) with Art Maxwell *Richard P. Von Herzen, WHOI • 2:30—2:50*
	ONR in the 90's *Fred E. Saalfeld, ONR • 2:50—3:10*
3:10 – 3:30	Break
	Art Maxwell and Woods Hole Oceanographic Institution—the MIT-WHOI Joint Program and tales from the WHOI Docks *A. Lawrence Peirson III, WHOI • 3:30—3:50*
	ODP/JOI *John A. Knauss, URI • 3:50—4:10*
	Oceanography in Texas and at the Institute for Geophysics *William J. Merrell, TAMU • 4:10—4:30*
	Graduate education in geophysics in the Department of Geological Sciences with The University of Texas Institute for Geophysics *Milo M. Backus, UT • 4:30—4:50*
5:30 – 7:00	RECEPTION

A Tribute to

Arthur E. Maxwell



Milestones in Marine Geophysics

Five Decades of Progress

The University of Texas at Austin • Institute for Geophysics • 28-29 September 1994

Contents

INSTITUTE FOR GEOPHYSICS
THE UNIVERSITY OF TEXAS AT AUSTIN

7:00 – 9:00 **Dinner — An Appreciation:**
Master of Ceremonies—Fred Spilhaus, AGU

An Appreciation from the Oceanographic Community
Ned A. Ostenso, NOAA

An Appreciation from the Joint Oceanographic Institutions
Arthur M. Nowell, UW

An Appreciation from the National Research Council
William J. Merrell, TAMU
Mary Hope Katsouros, OSB/NRC

An Appreciation from The University of Texas Institute for Geophysics
Ian W. D. Dalziel, UTIG

Thursday

September 29, 1994
Lila B. Etter Alumni Center, Grand Ballroom
Presiding— Cliff Frohlich, UTIG

9:00

High resolution 2-D and 3-D seismic surveying and coring on the New Jersey outer continental shelf: Late Quaternary sedimentation and sequence stratigraphy and links to the older shelf record
James A. Austin, Jr., UTIG • 9:00—9:20

Large igneous provinces: A perspective from oceanic plateaus and volcanic passive margins
Millard F. Coffin, UTIG • 9:20—940

Are plate tectonic cycles real? Rechecking the "pulse of the Earth"
Ian W. D. Dalziel, UTIG • 9:40—10:00

10:00 – 10:20 Break

Investigation of convergent margin structures using three-dimensional seismic reflection imaging techniques
Thomas H. Shipley, UTIG • 10:20—10:40

Melt delivery at mid-ocean ridges
Jan D. Garmany, UTIG • 10:40—11:00

Mantle convection on Earth and Venus
Dan P. McKenzie, Cambridge University • 11:00—12:00

12:00 – 1:00 Lunch

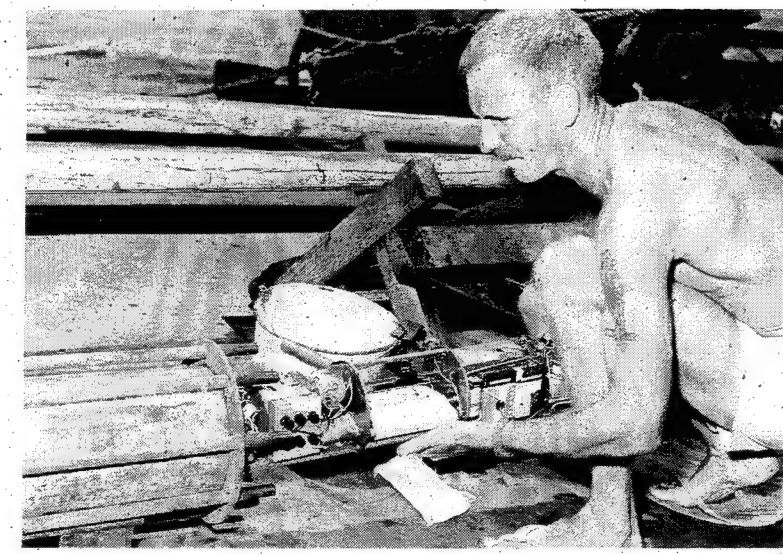
ARTHUR EUGENE MAXWELL

During his youth in Southern California, Arthur Eugene Maxwell was early lured by the sea. He joined the US Navy during World War II and served as a quartermaster assigned to working on nautical charts. After the navy he went to New Mexico State University and completed a BS in Physics with honors. He received an offer of a fellowship at Stanford University in physics. Fortunately, while driving back to New Mexico from an interview at Stanford, he read a two-page article about Scripps Institution of Oceanography in *Life* magazine. He decided to stop at Scripps and ended up spending a day talking to Walter Munk and another physicist, Dean Rusk. A week later, he drove up to Scripps, knocked on Walter's door and said, "Can I apply as a graduate student?" As a graduate, he worked with Walter Munk, Sir Edward Bullard, John Isaacs and Roger Revelle; in fact he was Roger Revelle's first graduate student.

He was fortunate during his first year (1949) to be assigned to work with Sir Edward Bullard, who was investigating heat flow. Heat flow studies became the basis of his thesis research. In 1950, during the *Midpac Expedition*, he helped to record the first successful heat flow measurements at sea. These, combined with successful recordings during the 1952 *Capricorn Expedition*, produced pioneering results in ocean geothermal measurements. He completed his masters degree in 1952 and left Scripps in 1955, while working on his Ph.D., to work at ONR on the organization for the International Geophysical Year.

Dr. Maxwell spent ten productive years (1955-1965) with the Office of Naval Research in Washington, D.C., where he held the positions of Head Oceanographer and Head of the Geophysics Branch. He pushed for the ONR support of academic oceanographic research. With Gordon Lill, Feenan Jennings and others, he produced the report "Ten Years in Oceanography" (TENOC), which spelled out a long-range plan for ONR to develop a strong academic program in oceanography. This helped the academic community gain access to a series of Navy research ships. He advocated and pressed for early support of submersible research using *Trieste*. He was responsible for the procurement of the *Trieste* by the Navy. His efforts encouraged the US Navy to develop a deep-submersible program. He helped establish the Interagency Committee on Oceanography (ICO). While at ONR Dr. Maxwell was active in the development of scientific ocean drilling through participation in the American Miscellaneous Society. It was that informal group that first proposed deep sea drilling, which eventually progressed to the Project Mohole, the Deep Sea Drilling Project, the Ocean Margin Drilling Program, and the Ocean Drilling Program. Dr. Maxwell was awarded the Navy's Meritorious Civilian Service and Superior Civilian Service Awards. He also received the Distin-

guished Civilian Service Award from the Secretary of the Navy for his work in locating the sunken submarine *Thresher.*



MidPac Expedition, 1950. Arthur E. Maxwell with temperature probe aboard the R/V Horizon. Mid-Pac Photo collection, SIO Archives, UCSD.

In 1965 he joined the staff of the Woods Hole Oceanographic Institution as Senior Scientist and Associate Director. During the next seventeen years, he progressed through the positions of Associate Director, Director of Research, and Provost.

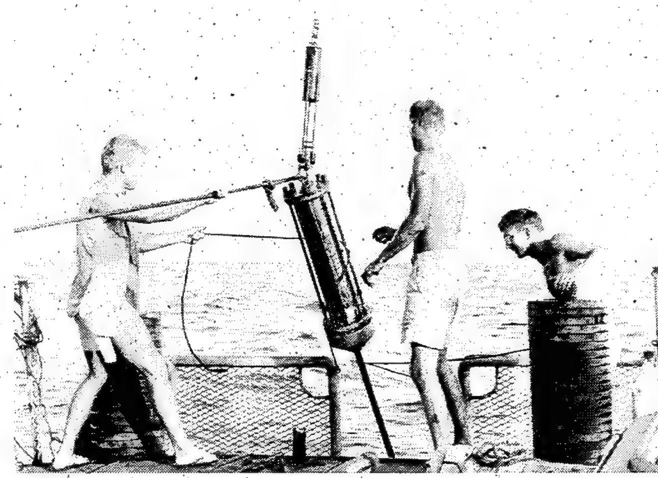
He was co-chief scientist, in 1968, with Richard Von Herzen, on Leg 3 of the Deep Sea Drilling Project using the drilling vessel *Glomar Challenger.* During that voyage, in the South Atlantic, they drilled a series of deep holes across the Mid Atlantic Ridge. The recovered data produced some of the first direct geologic evidence available to support the now widely accepted hypothesis of sea floor spreading and plate tectonics.

While at Woods Hole, he assisted Paul Fye, the Director, in establishing a joint graduate degree program in oceanography involving both MIT and WHOI. During his tenure at WHOI, the Quissett Campus was acquired and a substantive building construction program began. He was instrumental in arranging for the East Coast marine group of the U.S. Geological Survey to locate on the Quissett Campus. He also oversaw a solid growth of the scientific staff at the institution.

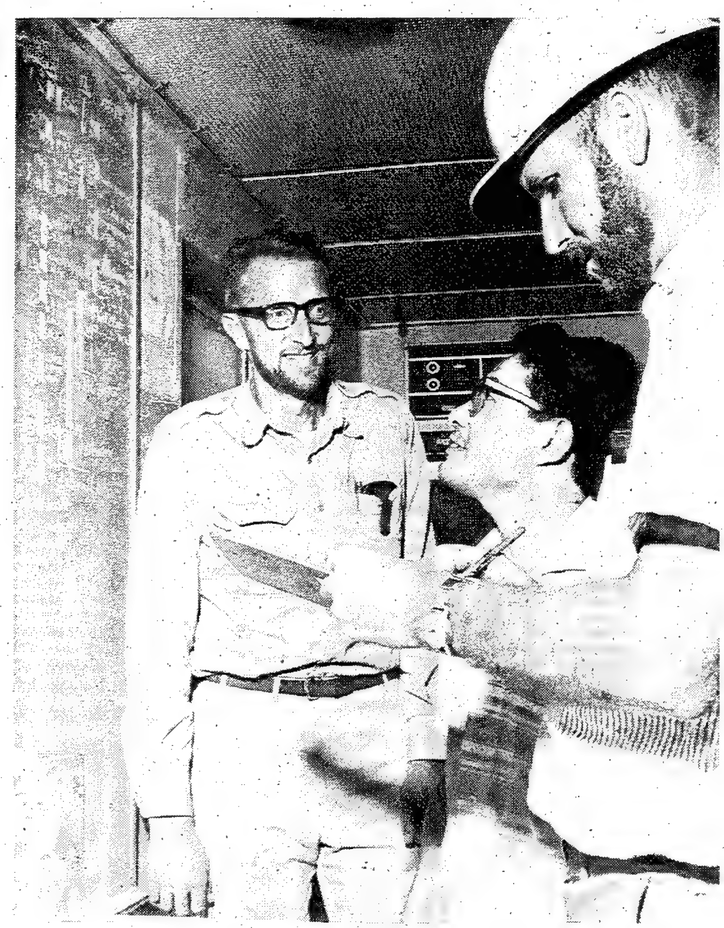
January 1, 1982, Dr. Maxwell came to The University of Texas at Austin as the first director of the newly formed Institute for Geophysics. His efforts have developed the Institute into one of the leading geology and geophysical research institutions in the world.

He was instrumental in relocating the research staff from Galveston to Austin, which led to an increase in research staff from 14 to 31; an increase in graduate student involvement from 10 to 49; increased interaction with other UT Austin departments and other universities, both national and international, and an increase in seismic data processing capabilities from a dedicated minicomputer system to supercomputer based commercial seismic data processing software and workstation based geophysical interpretation.

He was also responsible for increase in NSF funding to the Institute during his tenure from less than $500K to a high of $3.5M (1987). He proposed and obtained an annual Student Cruise allotment from State funds which has funded over 16 student training cruises. He was responsible for obtaining a $250K challenge grant from Palisades Geophysical Institute (PGI) and raising $250K matching funds to establish an endowment for the Ewing Worzel



Capricorn Expedition, 1952. Philip Jackson, Arthur Maxwell, Richard Blumberg. Temperature probe going overside on R/V SPENCER F. BAIRD.



Arthur Maxwell, Richard Von Herzen and Tsunemasa Saito aboard the Glomar Challenger during DSDP Leg 3.

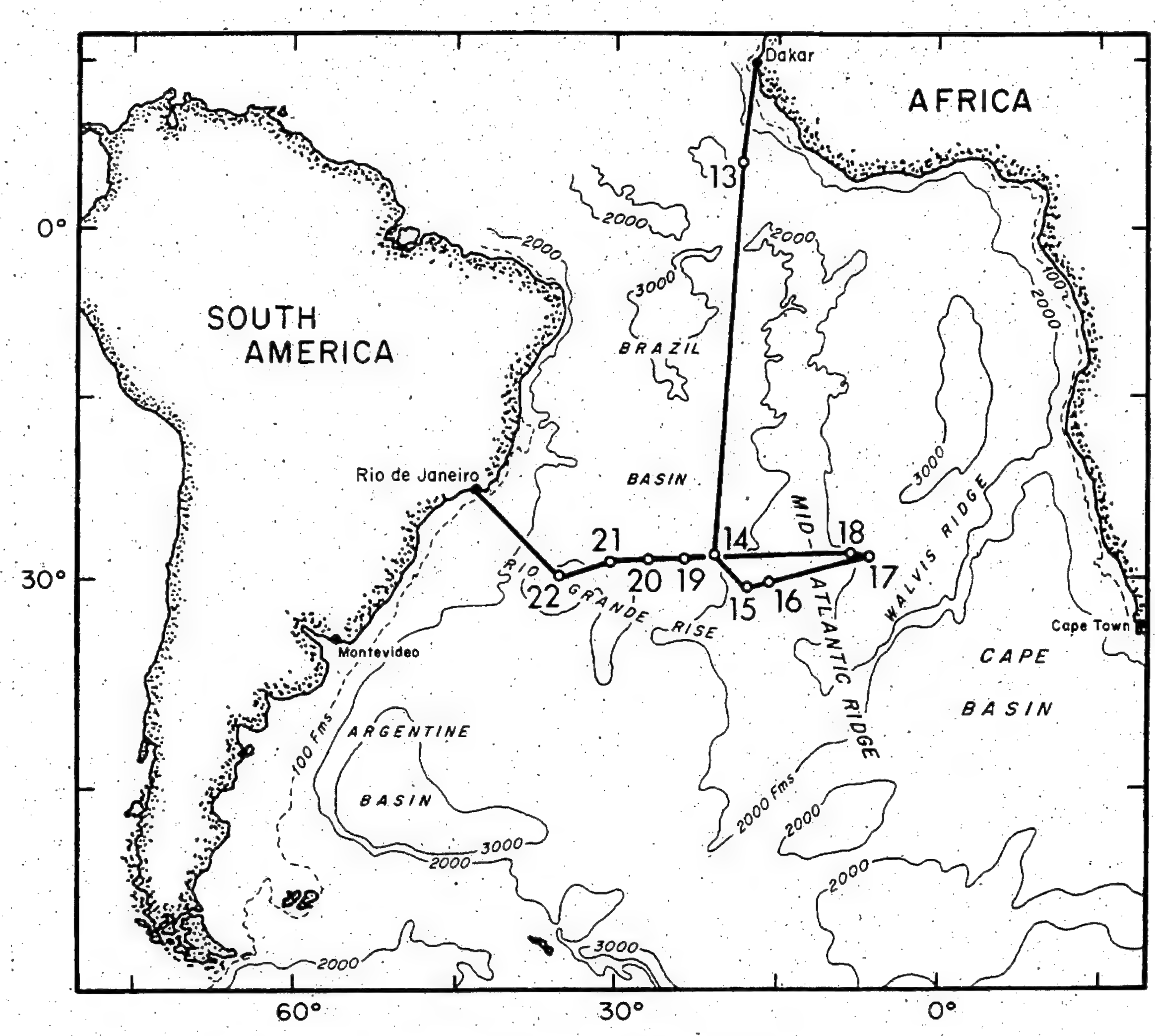
Fellowship Fund for student support. He also obtained a $300K grant from PGI which was matched to provide a $600K endowment for Postdoctoral fellowships support and a $300K grant from the G. Unger Vetlesen Foundation for research support.

He supported the UTIG acquisition of the first academic 3-D seismic survey; the development of the UTIG heat flow measurement tool and the development of the digital UTIG Ocean Bottom Seismometer.

He was instrumental in the Institute's becoming a member of JOIDES in 1982 and later providing a home and support for the JOIDES Office for two years (1990-1992). Through Maxwell's encouragement the JOI/USSAC science support program was established. UTIG housed the secretariat for program the first 5 years. Under his leadership the Institute provided a home and support for the initiation of the IRIS Data Management Facility. His efforts brought the CASERTZ airborne geophysical (Antarctica) experiment to UTIG and the success of CASERTZ has led to the establishment of the Support Office for Aerogeophysical Research (SOAR) facility at UTIG.

His participation in state, national, and international activities includes the Massachusetts Governor's Advisory Committee on Science and Technology, the National Sea Grant Review Panel, and the Alaska Governor's Commission for Ocean Advancement through Science and Technology. He has chaired both the US National Committee on Geology and the US National Committee for the International Union of Geodesy and Geophysics (IUGG), in addition to serving on the Finance Committee of IUGG. Dr. Maxwell has served on a number of National Academy of Sciences–National Research Council committees. President Nixon appointed him to The National Advisory Committee on Oceans and Atmosphere from 1972 to 1975, and he has headed the US Delegation to the Intergovernmental Oceanographic Commission. He was Chairman of the JOIDES Executive Committee and served on the JOI Board of Governors. He served on the Outer Continental Shelf/Environmental Studies Program Committee of the National Research Council. He is currently a member of the Sea Grant National Advisory Panel, the Academic Advisory Panel for a subcommittee of the Technology Transfer Intelligence Committee of the CIA, and the Gulf of Mexico Regional Research Board.

He has served on advisory committees and boards of many universities and institutions, including Harvard College, Department of Geological Sciences; Princeton University, Department of Geological and Geophysical Sciences; University of Miami, Rosenstiel School of Marine and Atmospheric Studies; University of Colorado, CIRES (Cooperative Institute for Research in Environmental Sciences); New Mexico State University, Department of Physics; Palisades Geophysical Institute; Marine Biological Laboratory, Woods Hole Oceanographic Institution and the Boston Museum of Science.



Location of the sites drilled during DSDP Leg 3

He was elected President of both the American Geophysical Union and the Marine Technology Society. In addition, he received the New Mexico University's Distinguished Alumni Award and the Outstanding Centennial Alumnus Award.

Art Maxwell's retirement represents the passage of an era of true deep sea explorers whose love of the sea took them into oceanography. The group of which he was a leader totally changed the way we look at the world. Art Maxwell occupied key positions at critical times during the "institutionalization" of oceanography in the United States. He has had many great achievements in his distinguished career. His contributions to setting the national agenda while at SIO, ONR, WHOI, NAS/OSB, AMSOC and UTIG are numerous. He set the style of civility and intellectual partnership between grantor and grantee, bureaucrat and scientist, professor and student, researcher and technician and extended these relationships to the international community. His staff, friends and colleagues remember him most for his patience, thoughtfulness, concern and professionalism that have greatly encouraged many, both as scientists and as individuals.

MILESTONES SPEAKERS

PAUL L. STOFFA

Acting Director, Institute for Geophysics
Professor, Department of Geological Sciences
The University of Texas at Austin

Paul L. Stoffa received his Ph.D. in Geophysics from Columbia University in 1974. His research has focused on the development of new seismic data acquisition and processing methods. His interests include seismic modelling, migration and inversion and one- and two-dimensional signal processing. As part of his research in the processing of seismic data, he has developed plane wave decomposition data analysis methods which improve velocity resolution and subsequent seismic imaging. He is currently a Professor in the Department of Geological Sciences at The University of Texas at Austin and the Acting Director of The University of Texas of Austin Institute for Geophysics.

JOHN G. SCLATER

Professor of Oceanography
Scripps Institution of Oceanography
University of California, San Diego

John G. Sclater received his B.S. from Edinburgh University and Ph.D. from Cambridge University. He is presently Professor of Geophysics at Scripps Institution of Oceanography. He was previously Associate Director and Senior Research Scientist at the Institute for Geophysics and Professor and Holder of the Shell Distinguished Chair in Geophysics in the Department of Geological Sciences at The University of Texas at Austin.

Dr. Sclater's original experience was with marine geophysical data, principally taking heat flow measurements at sea. He established a simple relation between heat flow, subsidence and age for the ocean crust and showed it could be accounted for by simple plate cooling models. In the immediate past, he has investigated the application of simple extensional models to the tectonic history of continental basins and shelves. Specifically, these studies involve examining the subsidence of heat flow through and thermal maturation history of the sediments on the shelves. A problem of particular interest was the relation between the throw on the faults observed on seismic sections across extensional basins and the amount of extension necessary to account for the subsidence, heat flow and maturation of these sediments. All these studies involved interpretation of multichannel seismic sections. Areas of current interest include modeling of deformation by block faulting, the application of geoid anomalies to determining the tectonic history of the ocean floor and the use of heat flow measurements in the search for hydrocarbons on the continental shelf of the northern Gulf of Mexico.

He has served on many national and international committees. His numerous awards include Swiney Lecturer, Edinburgh University, 1975-1976; Rosenstiel Award, 1979, Shell Distinguished Professorship, 1983-1988; Bucher Medal, American Geophysical Union, 1985; American Association of Petroleum Geologists Distinguished Lecturer, 1987-1988; Fellow, Geological Society of America; Fellow, American Geophysical Union; Fellow, The Royal Society, London, U.K.; and Member, National Academy of Sciences.

He has served as Chief Scientist for numerous oceanographic scientific expeditions and worked with over 30 Masters or Ph.D. level students. He has authored over 150 articles and technical reports.

Gustaf Arrhenius

Professor of Oceanography
Scripps Institution of Oceanography
University of California, San Diego

Gustaf Arrhenius, born in Stockholm, Sweden, in 1922, came to the United States in 1952 to join the staff of Scripps Institution of Oceanography in La Jolla, California as a visiting research oceanographer. He was appointed to the faculty in 1956 and participated in the early development of the San Diego campus of the University of California. Presently he serves as Professor of Oceanography at Scripps, and as a member of the Electrical and Computer Engineering Department.

At SIO/UCSD, Dr. Arrhenius has conducted research in oceanography, space science, solid state physics and biogeochemistry. His oceanographic studies include the relationship between the wind-driven ocean circulation and the recording of climate change in deep sea sediments. Other research by Dr. Arrhenius concerns the formation of minerals in the ocean, the relationship between crystal structure and superconductivity, the condensation and aggregation of matter in outer space, the origin and evolution of the solar system, and the origin of life.

In 1967, he was selected by the National Aeronautics and Space Administration as a principal investigator on the lunar samples subsequently collected during the Apollo missions, and from 1969 to 1971, he was a member of NASA's Lunar Sample Analysis Planning Team. Presently, the members of Dr. Arrhenius' research group in Scripps are focusing much of their interest on those processes responsible for the formation of simple organic compounds that may have served as building blocks for biomolecules on early Earth, and the geochemical processes responsible for concentrating, ordering and polymerization of such single compounds to form more complex molecular systems with biofunctionality.

Since joining the Scripps faculty, Dr. Arrhenius has served with UCSD as Chairman of the Division of Marine Geology and Geochemistry, Chairman of the Department of Earth Sciences, Director Pro Tem of the Interdepartmental Laboratory of Spaces Sciences, Associate Director of the Institute for the Study of Matter, and Associate Director of the Institute for Pure and Applied Physical Sciences. He is a founding member of NASA's current Specialized Center of Research and Teaching in Exobiology at California Space Research Institute, SIO-UCSD.

Before coming to the United States, Dr. Arrhenius served as a member of the scientific staff of the Skagerak Expedition 1946 and the Swedish Deep Sea Expedition (1947-48), and was a research fellow with the Swedish National Research Council until 1953, while doing research on the sediment cores retrieved from the East Equatorial Pacific.

Arrhenius received his Ph.D. from the University of Stockholm in 1953. He has published more than 200 scientific and technical contributions in his fields of research, and has served on various committees of international organizations, the federal government and the university.

Arrhenius is a foreign member of the Swedish Royal Academy of Sciences, a member of the International Academy of Astronautics, the (Russian) Akademiya Tvorchestva, the Geophysical Society of Sweden, the Geological Society of Stockholm, the Geochemical Society, the American Geophysical Union, the International Union of Geochemistry and Cosmochemistry, and the Meteoritical Society. In 1957, he was the recipient of a Guggenheim Fellowship and in 1961 of the American Chemical Society's PRF Award. He was elected a Fellow of the American Mineralogical Society in 1973, a Fellow of the American Association for the Advancement of Science in 1981 and a Fellow of the Geological Society of India in 1989. He is a recipient of the Albatross Medal and, from Akademiya Tvorchestva, the Svante Arrhenius Prize and Academy Medal.

Richard P. Von Herzen

Senior Research Scientist
Woods Hole Oceanographic Institution

Richard P. Von Herzen is a Geophysicist and Senior Scientist at Woods Hole Oceanographic Institution. He received his B.S. at the California Institute of Technology, M.A. at Harvard University and Ph.D. at the Scripps Institution of Oceanography. After receiving his Ph.D., he worked at Scripps Institution of Oceanography and then was employed as Deputy Director, Office of Oceanography, UNESCO, Paris, France before moving to Woods Hole Oceanographic Institution.

Richard Von Herzen's research interests include heat flow, electromagnetic induction and seafloor tectonics. He was honored as a Fellow of the American Geophysical Union in 1985. He has been very involved since the early days of JOIDES and has served on many professional committees and panels.

He has participated in 35 oceanographic cruises, serving as Chief Scientist for 10 of the cruises, and 4 limnological cruises in African and Swiss lakes. He has also been co-chief scientist for three of the four Deep Sea Drilling Project and Ocean Drilling Program cruises he has participated in (Legs 3, 70, and 118). He has authored or coauthored 123 scientific papers in geophysics, especially in geothermics.

Fred E. Saalfeld

Deputy Chief of Naval Research/Technical Director
Office of Naval Research

Dr. Fred E. Saalfeld was born in Joplin, Missouri. He received his B.S. degree cum laude with majors in Chemistry, Physics and Mathematics from Southeast Missouri State University in 1957. Dr. Saalfeld was awarded his M.S. and Ph.D. degrees with a major in Physical Chemistry and minors in Inorganic Chemistry and Mathematics from Iowa State University in 1959 and 1961, and remained one year at Iowa State as an Instructor.

Dr. Saalfeld joined the Naval Research Laboratory (NRL) in 1962, where he conducted and directed research in physical chemistry. From 1963 to 1973, he headed the Mass Spectrometry Section where his research led to the innovative systems for atmospheric monitoring and life support now widely used in nuclear submarines, firefighting gear, spacecraft and other equipment using recirculated air. From 1974 to 1976, he directed the Physical Chemistry Branch, a group of 25 scientists. In 1976, Dr. Saalfeld was selected as Superintendent of the Chemistry Division, where he was responsible for approximately 350 chemists and a program of more the $16M. In 1979 and 1980, Dr. Saalfeld was the Chief Scientist and Scientific Director at the Office of Naval Research (ONR) Branch Office, London. In 1982, he was NRL's Acting Associate Director of Research for Material Sciences and Component Technology, directing more than 900 scientists and a $90M program. Dr. Saalfeld was appointed the Director of the ONR Research Department in 1982 and the Associate Director of ONR in 1985. In these positions he was responsible for the Navy's $220M contract research program, largely conducted at universities. From 1987 until 1993, Dr. Saalfeld was Director of ONR, responsible for the Navy's basic research effort and the Navy's corporate laboratory, NRL.

In 1993, Dr. Saalfeld was appointed Technical Director of ONR and Deputy Chief of Naval Research, where he is responsible for the Navy and Marine Corps $1.5B science and technology program, including basic research, exploratory and advanced technology development conducted in federal and private laboratories, academia and industry.

Dr. Saalfeld is a charter member of the Senior Executive Service. In 1986, President Reagan conferred on him the Presidential rank of Meritorious Executive, and in 1989, President Bush conferred on him the Presidential Distinguished Executive Rank. Other awards include the Navy Meritorious and Superior Civilian Service Awards, Southeast Missouri State University Alumni Merit Award, and the Captain Robert Dexter Conrad Award, the Navy's highest award for scientific achievement. Washington Technology named him one of the area top ten technologists in 1989; and he was selected as Federal Executive of the Year in 1991 by the Federal Executive Institute.

Dr. Saalfeld has authored or coauthored more than 450 research papers, reports and presentations. He is active in many scientific societies, including the Society for Applied Spectroscopy, the American Society for Mass Spectrometry, and the American Chemical Society. He is a Fellow of the American Association for the Advancement of Science. He has served as Secretary of the American Society for Mass Spectrometry, as the President of the Chemical Society of Washington, as a board member of many American Chemical Society Committees, and as a consultant to the Joint Board/Council Committee of Science.

A. Lawrence Peirson, III

Associate Dean and Registrar
Woods Hole Oceanographic Institution

After receiving M.S. in Geology from Stanford University in 1956, Jake Peirson spent the next years working as a Regional Geologist for Creole Petroleum Corporation in Caracas, Venezuela. He received his M.B.A. (with honors) from Boston University in 1967.

He came to the Woods Hole Oceanographic Institution as Assistant to the Director and worked on the Institution's first major private development program. He then became the Assistant to the Dean of Graduate Studies and was responsible for setting up and administrating the Education Office, which was newly established in 1968. Progressing to Assistant Dean and Registrar and eventually his present position, he is responsible for the coordination, administration, and the fiscal management of the Institution's education programs, which include a joint program with the Massachusetts Institute of Technology, postdoctoral and summer fellowship programs, and other student training programs. He serves as primary liaison with faculty and administration at both Massachusetts Institute of Technology and WHOI and provides student counsel.

His other professional activities have included Executive secretary, National Oceanographic Graduate Program "Deans' Meetings" - originator of concept for these meetings, designed to focus attention on issues of concern to Deans of graduate oceanography programs 1980-88; Member, Office of Naval Research Graduate Fellowship Review Panel, 1986-present (Chairman Oceanography panel, 1988-present). He was a participant in Intergovernmental Oceanographic Commission Workshop on the preparation of a marine science syllabus for secondary schools, 1978.

His professional memberships include: American Association of Petroleum Geologists, American Institute of Professional Geologists (charter), American Association for the Advancement of Science, American Geophysical Union, National Marine Educators Association and The Oceanography Society.

John A. Knauss

Dean and Professor Emeritus
Graduate School of Oceanography
University of Rhode Island

John A. Knauss began his career as an oceanographer in 1947 at the Navy Electronics Laboratory in San Diego and later worked as an oceanographer for the Office of Naval Research before earning his Ph.D. from the Scripps Institution of Oceanography. His dissertation was on the Pacific Equatorial Undercurrent which he was the first to map in 1958 as head of a two-ship expedition. His major area of oceanographic research has been the study of ocean circulation and he has led expeditions in the Atlantic and Indian Oceans as well as the Pacific. For a 20 year period from 1947 to 1968 he spent from 1-4 months a year at sea aboard oceanographic research vessels. He participated in both the International Geophysical Year and the International Indian Ocean Expedition.

In 1962 he went to the University of Rhode Island as Dean of the new Graduate School of Oceanography. In 1969 he was given the additional title of Provost and later Vice President for Marine Programs, positions he held until 1987. While at URI, he worked closely with Senator Claiborne Pell in the establishment of the Sea Grant program and was a cofounder of the Law of the Sea Institute. During his tenure as Dean, the Graduate School of Oceanography became one of the major oceanographic programs in the US.

He was appointed by President Johnson as a member of the Stratton Commission (Commission on Marine Science, Engineering and Resources). As a member he chaired the panel that brought forth recommendations that later led to the Coastal Zone Management Act. He was later appointed by President Carter to be a member of NACOA (National Advisory Committee on Oceans and Atmosphere). He was reappointed as chair of NACOA by President Reagan.

In 1989 he was appointed by President Bush as Administrator of NOAA (National Oceanic and Atmospheric Administration), a position he held until 1993. During this period he also served as US Commissioner to the International Whaling Commission.

Knauss has held a number of professional offices and served on many advisory committees. These include President of the Oceanographic section of the American Geophysical Union, President of the Association of Sea Grant Colleges, Council Member of the American Meteorological Society, Chair of the National Academy of Sciences Committee on Oceanography, Chair of the Marine Division of the National Association of State Universities and Land Grant Colleges and First Vice Chair of the Intergovernmental Oceanographic Commission. He also served a number of years as the chief adviser on marine science to the US delegation to the Law of the Sea Conference.

He is a Fellow of the American Geophysical Union, the American Association for the Advancement of Science and the Marine Technology Society. In 1988 Congress named the Sea Grant Fellows program the Dean John A. Knauss Fellowship program.

He has published two text books, several book chapters and more than 50 papers on oceanography and marine policy.

He is currently dividing his time between the University of Rhode Island (summers), where he is Dean and Professor Emeritus; and Scripps (winters), where he is a Research Associate.

William J. Merrell

Vice Chancellor for Strategic Programs
The Texas A&M University System

Dr. William Merrell was appointed Vice Chancellor for Strategic Programs of The Texas A&M University System in September 1993. Merrell also holds appointments as Professor of Oceanography at Texas A&M University, Professor of Marine Sciences at Texas A&M University at Galveston and Rear Admiral (Ret.) in the United States Maritime Service.

Immediately preceding his present assignment, Merrell served as Vice President for Research Policy of Texas A&M University. He was President of Texas A&M University at Galveston from July 1987 to January 1992. Before that he was Assistant Director of the National Science Foundation where he was in charge of the Geosciences Directorate which is comprised of the Divisions of Atmospheric Sciences, Earth Sciences, Ocean Sciences, and Polar Programs. While at the National Science Foundation, he was on leave from Texas A&M University where he had served as Director of the Division of Atmospheric and Marine Sciences, and Principal Investigator of the Ocean Drilling Program.

Merrell received B.S. and M.A. degrees in physics from Sam Houston State University and a Ph.D. in oceanography from Texas A&M University. Merrell has been named a Distinguished Alumni by Sam Houston State University. He received the Distinguished Member Award for Research Achievement from the Texas A&M University Chapter of Sigma Xi, the Distinguished Achievement Award from the Geosciences and Earth Resources Council, and the Distinguished Service Award of the National Science Foundation for "his lasting impact on the course of American Science."

Dr. Merrell has published scientific papers in many aspects of marine sciences. His latest ocean science contributions are on the circulation and sediment transport of the Texas Continental Shelf and Slope. In science policy, he has written articles and given speeches on the development of scientific programs to examine the

Earth's climate changes, on the need for improved academic-federal partnerships in oceanography, and on the role of basic research in economic competitiveness. Merrell serves on committees or as a director of a number of national and international scientific organizations.

Milo M. Backus

Professor, Department of Geological Sciences
Senior Research Scientist, Institute for Geophysics
The University of Texas at Austin

Milo M. Backus is a Professor of Geophysics at The University of Texas at Austin. He received his B.S. in Geology and Geophysics and Ph.D. in Geophysics from Massachusetts Institute of Technology. His major research interest is quantitative interpretation of geophysical data applied to petroleum exploration.

Before coming to Austin he was a research geophysicist with Geophysical Service Inc., Dallas, TX (1955-1974) where he also served as Director of Research (1962) and Vice-President (1965). He currently holds the Shell Oil Companies Foundation Distinguished Chair in Geophysics at The University of Texas. His numerous honors and awards include Society of Exploration Geophysicists (SEG) Best Paper Award (1959); European Association of Exploration Geophysicists Conrad Schlumberger Award (1975); SEG President (1979-1980); SEG Distinguished Lecturer (1985); SEG Honorary Member (1988), SEG Maurice Ewing Gold Medal (1990) and Offshore Technology Conference Individual achievement award (1992).

A. F. Spilhaus, Jr.

Executive Director
American Geophysical Union

Fred Spilhaus did both his graduate and undergraduate work at the Massachusetts Institute of Technology receiving a Bachelor's Degree in Chemical Engineering, Master's Degree in Geology and Geophysics, and a Ph.D. in Oceanography. He worked at the Central Intelligence Agency for two years after graduate school, then joined the American Geophysical Union staff. He served AGU as Assistant Executive Director from 1967-1970 and has been Executive Director of the AGU since 1970. He has served under fifteen AGU presidents and with thousands of volunteers. He has also been a volunteer himself.

Spilhaus has been Secretary of the U.S. National Committee for the International Union of Geodesy and Geophysics since 1970. Since 1987 he has been a member of the Finance Committee of the IUGG. He has also served a variety of scientific, professional, and trade associations. Among them he has been President of the Association of Earth Science Editors, the Council of Engineering and Scientific Society Executives, and the Philosophical Society of Washington, Chairman of the Convention Liaison Council and its Board for the certification of meeting professionals, and a member of the Executive Committee of the Professional and Scholarly Publishing Division of the Association of American Publishers. He also serves on the Governing Board of the American Institute of Physics, and as a member of the Board of Directors of the Renewable Natural Resources Foundation. He was President of the Cosmos Club in 1993.

Ned A. Ostenso

Assistant Administrator
Office of Oceanic and Atmospheric Research
National Oceanic and Atmospheric Administration

Dr. Ned A. Ostenso is currently the Assistant Administrator for Oceanic and Atmospheric Research, National Oceanic and Atmospheric Administration (NOAA). He was named to this position in October 1989. He has also served as NOAA's Chief Scientist since October 1989.

Dr. Ostenso was the Deputy Assistant Administrator for Research and Development and Director of the National Sea Grant College Program. He came to the Department of Commerce in 1977 from a post as Deputy Director and Senior Oceanographer of the Ocean Science and Technology Division, Office of Naval Research. He served as Assistant Presidential Science Adviser in the Office of Science and Technology of the Executive Office in 1969-70 and on the Faculty of the University of Wisconsin,

Department of Geology and Geophysics from 1962 to 1966.

He has had broad research experience in solid-earth and marine geophysics in North America, Africa, Europe, and Antarctica. His research activities have resulted in over 50 published scientific papers. Dr. Ostenso's contributions to earth and marine sciences have brought him numerous honors, including having a major mountain in Antarctica and a seamount in the Arctic Ocean named after him. He holds memberships in scientific professional societies and advisory committees; and meritorious service awards from the Department of Defense, the Navy Department, and the National Academy of Sciences.

Dr. Ostenso received a Bachelor of Science Degree in 1952, a Master of Science Degree in 1953, and a Doctorate in 1962, all from the University of Wisconsin. During this period, he was also associated with the Woods Hole Oceanographic Institution, the Lamont-Doherty Geological Observatory of Columbia University, and the Arctic Institute of North America. He also served as a Signal Corps meteorological project officer at the U.S. Army Arctic Center.

He attended Johns Hopkins School for Advanced International Studies and was an American Political Science Association Fellow in the U.S. Senate and the U.S. House of Representatives, where he developed the National Earthquake Hazard Reduction and National Climate Program Acts and worked on Law of the Sea and strategic minerals issues.

ARTHUR M. NOWELL

Director
School of Oceanography
University of Washington

Arthur Nowell is a Professor of Oceanography and has been Director of the School of Oceanography at the University of Washington since 1987. Dr. Nowell received his Master of Arts degree in Geography from Trinity College Cambridge, and his doctorate in Fluvial Hydraulics from the University of British Columbia. His research interests include biological sedimentary dynamics, geophysical boundary layers, sediment transport, and oceanic particulate dynamics. He has published over 50 papers in his research areas and in addition, has undertaken several studies on human resource issues in oceanography and changes in education at the undergraduate and graduate level. Dr. Nowell has served as a member of the National Research Council's Ocean Studies Board since 1990. He recently served as chairman of an NRC committee that reviewed NOAA's Sea Grant program. He acted as Interim President of the Joint Oceanographic Institutions, Inc. in 1993 and is completing his term as Chairman of the JOIDES Executive Committee. Recently, Dr. Nowell participated in research cruises in the Arctic, studying high energy boundary layer flows in the deep ocean and in ice-covered seas.

MARY HOPE KATSOUROS

Director
Ocean Studies Board of the National Research Council

Mary Hope Katsouros is the Director of the Ocean Studies Board of the National Research Council. She holds a law degree from the Georgetown Center for Law with undergraduate and master's degrees from the George Washington University. Her research interests include pollutants in the marine environment, especially inputs, fates and effects of oil spills. She is also interested in the law of the sea and its affect on resource management and marine scientific research. Ms. Katsouros has served as an advisor to the Department of State on law of the sea issues and to the congressional Office of Technology Assessment on oil spills. The Ocean Studies Board serves as an independent advisor to the federal government on a broad range of ocean science and policy issues. As director, Ms. Katsouros has produced over 45 National Research Council reports on issues spanning the oceanographic research disciplines and linking ocean science and policy. Some of her most recent studies include the topics of the ocean's role in global change, the effects of low-frequency sound on marine mammals, the application of analytical chemistry to oceanic carbon cycles, the global ocean observing system, marine fisheries science and management, biological diversity in marine systems, and an ongoing symposium series on coastal science and policy interactions.

Ian W. D. Dalziel

Senior Research Scientist and Associate Director
Institute for Geophysics
Professor, Department of Geological Sciences
The University of Texas at Austin

Ian W. D. Dalziel received B.Sc. (First Class Honors) from the University of Edinburgh in 1959 and his Ph.D. from the University of Edinburgh in 1963.

His development of the hypothesis that the Pacific margins of North America and East Antarctica-Australia were juxtaposed prior to the opening of the Pacific Ocean basin, put forward in 1991 with Eldridge Moores of the University of California at Davis, has led to an entirely new scenario for the tectonic history of the Earth before the amalgamation of Pangea.

He is the recipient of numerous fellowships and awards, among them are the Geological Society of London's Murchison Medal (1992); John Simon Guggenheim Memorial Fellowship 1976-77 to undertake "Comparative Studies in Structural Geology" (based in Swiss Federal Institute (ETH), Zurich, Switzerland); Swiney Lecturer, University of Edinburgh (1978); Corresponding Member of the Geological Association of Argentina (elected, 1980) and Erskine Fellow, University of Canterbury, New Zealand (1993).

He has over 30 years field experience especially in Caledonides, Canadian Shield, Andes and Antarctica. He was the leader of Field Trip T180 of 28th International Geological Congress on Tectonics of Scotia Arc.

His shipboard experience includes numerous science cruises, many as Senior/Chief Scientist. Co-Chief Scientist on Leg 36 - Scotia Sea/Falkland Plateau Area.

He is a Geological Society of America (fellow); Geological Society of London (fellow); Geological Association of Argentina (corresponding member); Geological Association of Chile (fellow); and American Geophysical Union (member).

His membership in national and international committees include the Polar Research Board, National Research Council and U.S. National Committee on Antarctic Research (1988-1992); Convener, Group of Specialists on the Structure and Evolution of the Antarctic Lithosphere, Scientific Committee on Antarctic Research, International Council of Scientific Unions (1986-present); Member of Tectonics Panel, Ocean Drilling Program (1986-1987); Chairman, Tectonics Panel, Ocean Drilling Program (1988-1990); Delegate to Scientific Committee on Antarctic Research of International Union of Geological Sciences (1987-present).

Dan Peter McKenzie

Professor of Earth Science
Cambridge University

Dan Peter McKenzie received his B.A., M.A., and Ph.D. from the Cambridge University and is presently a Fellow of Kings College, Cambridge, and Professor of Earth Sciences in the Department of Earth Sciences at Cambridge. He has held temporary positions at Scripps Institution of Oceanography, California Institute of Technology, Lamont-Doherty Geological Observatory, Princeton University, Massachusetts Institute of Technology, Harvard University, Woods Hole Oceanographic Institution, University of Chicago, The University of Texas at Austin, and European Professor, Ecole Normale Supérieure, Paris.

His honors include Fellow of the American Geophysical Union; Fellow of the Royal Astronomical Society; Honorary Member, Geological Society of France; Life Member, Seismological Society of America; Fellow of the Geological Society of London (1991 Chartered Geologist); and Life Member of the Geological Society of America.

Science at UTIG

High-Resolution 2-D and 3-D Seismic Surveying and Coring on the New Jersey Outer Continental Shelf: Late Quaternary Sedimentation and Sequence Stratigraphy and Links to the Older Shelf Record

James A. Austin Jr
Senior Research Scientist

The distribution and nature of late Quaternary periglacial sediments, the history of post-Wisconsin sedimentation, and the relationships of late Pleistocene to earlier Quaternary and Neogene sequence stratigraphy offshore New Jersey are the foci of ongoing studies using Huntec® seismic reflection profiling and coring and regional multichannel seismic (MCS) reflection profiles collected by industry.

In this region, 2-D seismic surveys have delineated two wedges of late Quaternary sediment, one occupying the mid-shelf and another extending south from the Hudson apron along the shelf edge. The base of the outer-shelf wedge is defined by a prominent seismic reflector ("R"). A 1989 3-D Huntec survey of the outer-shelf wedge, combined with piston and gravity coring, has revealed two prominent, mappable reflectors between R and the sea floor. The upper reflector delineates a system of meandering channels apparently draining obliquely (southward) toward the shelf edge. Correlation with late Quaternary glacial history developed from studies on land suggests that R is an erosional surface formed at the last lowstand of sea level and that the outer-shelf wedge formed from a series of rapid depositional events related to post-Wisconsin maximum stages of glacial melting, interrupted by one or more erosional episodes as implied by the channels.

A second Huntec survey, conducted in the same general area in 1993, has acquired additional regional/2-D and 3-D profiles, along with a suite of vibra-cores. Both 1989 and 1993 3-D grids are located within the regional framework of east-west profiles, spaced 1 nmi apart. The 1993 3-D grid was also located to image portions of both outer- and mid-shelf sediment wedges. Preliminary examination of the new profiles shows more than one channeled surface within the sediment wedges, confirming the occurrence of multiple erosional episodes during their formation. Vibra-cores have confirmed that the core of the outer wedge, into which channels are cut, consists of stiff, sparsely fossiliferous silty clay with a fauna indicative of mid-shelf depths. By contrast, channels in the mid-shelf wedge are cut into sand and filled with silty clay having an estuarine fauna. The clay is overlain by sand rich in shell fragments, and the channels are cut into medium-coarse sand in which shell fragments are rare or absent. Both sands contain mid-shelf benthic foraminiferal faunas. Physical properties (velocity, bulk density) measurements on the cores permit calibration of the Huntec records, while biostratigraphy and AMS C-14 dating in progress should establish environmental history and chronology.

Late Quaternary sedimentation history can be linked to the older (deeper) Pleistocene and pre-Pleistocene shelf record by comparing the Huntec records with MCS records of varying seismic resolution and with results of recently completed (Leg 150) and proposed ODP drilling. A low-resolution, but extensive, grid of industry MCS data is currently being interpreted and mapped. A high-

resolution MCS survey is planned for 1995 as a component of the STRATAFORM (STRATA FORmation on Margins) initiative of the Office of Naval Research (ONR). The goal of STRATAFORM is to understand the creation of the stratigraphic record on continental shelves and slopes as the product of geological processes. The planned survey will also incorporate hazards-type surveys of a number of proposed ODP shelf drill sites, setting the stage for the completion of a transect of boreholes across the New Jersey Coastal Plain, shelf and slope. The Coastal Plain and slope components of the transect have already been drilled (ODP Legs 150 and 150X).

This work is funded by the Office of Naval Research, with supplemental support for high-resolution surveys in the vicinity of proposed ODP sites from the National Science Foundation, through JOI-USSAC.

Large Igneous Provinces: A Perspective From Oceanic Plateaus And Volcanic Passive Margins

Millard F. Coffin
Research Scientist

Large igneous provinces (LIPs) are a continuum of voluminous iron and magnesium rich rock emplacements which include continental flood basalts and associated intrusive rocks, volcanic passive margins, oceanic plateaus, submarine ridges, seamount groups, and ocean basin flood basalts. Such provinces do not originate at "normal" seafloor spreading centers. We analyze dimensions, crustal structures, ages, and emplacement rates of representatives of the three major LIP categories—Ontong Java and Kerguelen-Broken Ridge oceanic plateaus, North Atlantic volcanic passive margins, and Deccan and Columbia River continental flood basalts. Crustal thicknesses range from 20 to 40 km, and the lower crust is characterized by high (7.0-7.6 km/s) compressional wave velocities. Volumes and emplacement rates derived for the two giant oceanic plateaus, Ontong Java and Kerguelen, reveal short-lived pulses of increased global production: Ontong Java's rate of emplacement may have exceeded the contemporaneous global production rate of the entire mid-ocean ridge system. The major part of the North Atlantic Volcanic Province lies offshore, and demonstrates that volcanic passive margins belong in the global LIP inventory. Deep crustal intrusive companions to continental flood volcanism represent volumetrically significant contributions to the crust. A complex mantle circulation must account for the variety of LIP sizes—the largest originating in the lower mantle, and smaller ones developing in the upper mantle. This circulation coexists with convection associated with plate tectonics, a complicated thermal structure, and at least four distinct geochemical/isotopic reservoirs. LIPs episodically alter ocean basin, continental margin, and continental geometries, and affect the chemistry and physics of the oceans and atmosphere, with enormous potential environmental impact. Despite the importance of LIPs in studies of mantle dynamics and global environment, scarce age and deep crustal data necessitate intensified efforts in seismic imaging and scientific drilling in a range of such features.

Are Plate Tectonic Cycles Real? Rechecking The "Pulse Of The Earth"

Ian W. D. Dalziel
Senior Research Scientist and Associate Director

Recent geologic correlations between Precambrian rocks of Laurentia and East Antarctica-Australia and South America have led to a new and testable scenario for the opening of the Pacific Ocean basin and the amalgamation of Gondwana. This in turn allows a fresh look to be taken at the so-called supercontinental cycle over the past 1 billion years. Rodinia, the supercontinent formed during Grenvillian orogenesis appears to have existed for approximately 250 my, while another supercontinent, as yet unnamed, may have existed fleetingly towards the end of Precambrian times. The suggestion that Laurentia then collided with the proto-Andean margin of South America in mid-Ordovician and again in Devonian times, leads to the possibility that two Laurentia-Gondwana "supercontinents" were formed and then fragmented during the Paleozoic Era prior to the amalgamation of Pangea in the Ouachita-Alleghenian orogeny. These events appear to be more like the chance encounters of continental masses moving on a dynamic earth of constant radius than the reflection of a tectonic "cycle."

The concept of global orogenies, Umgrove's "pulse of the earth", has fallen into disfavor since the advent of plate tectonics in the 1960's and 1970's. However, the suggested Laurentia-Gondwana collisions during early and mid-Paleozoic times, like the Ouachita-Alleghenian event at the end of the Paleozoic Era, correlate with major sequence boundaries in cratonic interiors. There may, therefore, be more to old ideas regarding close interaction between global tectonic and environmental changes than has recently been acknowledged.

Investigations of Convergent Margin Structures Using Three-Dimensional Seismic Reflection Imaging Techniques

Thomas H. Shipley
Senior Research Scientist

Structural evolution and fluids are inextricability linked in convergent margin accretionary prisms. In these environments tectonically induced burial rates of 10 km/m.y. are not unusual. It is well known that abnormally high pore-fluid pressure greatly reduces rock strength and influences fault mechanics. While the basic geometry of accretionary prisms is well documented, the internal structure that relates to the tectonic processes is only imaged in a few exceptional cases. Thus the basic structural evolution in accretionary prisms is poorly known. To help resolve some of these issues we adapted conventional 3-D seismic imaging techniques to this problem. We have recorded 3-D seismic reflection data sets from two diverse accretionary prisms, Costa Rica and Barbados, which share processes common to mud-dominated systems.

The Costa Rica 9 x 23 km data set was collected in 1987 along the Middle America Trench off the Nicoya Peninsula. Massive dewatering of the underthrust section is postulated within a few kilometers of the trench. Mud volcanoes and diapirs are common. Bright-spot fluid accumulations, including minor gas, occur at the slope cover-accretionary prism contact. Major through-going out-of-sequence faults apparently produce efficient paths for migration of fluids from deep levels of the prism to the lower slope. There is good evidence for forearc extension coeval with frontal accretion and underplating.

The Barbados 5 x 25 km data set was collected in 1992 over a portion of the lower slope examined in two DSDP/ODP drilling programs. The decollement is usually a compound negative-polarity reflection modeled as a low-velocity, high-porosity zone less than ~14 m thick. We infer that the seismically defined fault is a thin, high-porosity zone and is thus an undercompacted, high-fluid-pressure dilatant section. Map-view variations in seismic-reflection waveform and amplitude illustrate complex patterns of fault-zone fluid content and fluid pressure. Several areas of positive-polarity fault reflections define square kilometre-sized regions inferred to be lower porosity sections producing strong asperities in an otherwise weak fault. ODP Leg 156 drilling in this area in June and July 1994 discovered fluid pressures in the decollement at near lithostatic values and abnormally high porosities.

Melt Delivery at Mid-Ocean Ridges

Jan G. Garmany
Senior Research Scientist

In April and May of 1993, Yosio Nakamura and Jan Garmany from UTIG and Yann Hello from the French research organization ORSTOM conducted an ocean bottom seismograph (OBS) survey of the East Pacific Rise near 9° 30' N. The principal goal of the cruise was to find evidence for the presence of trapped melt near the base of the oceanic crust. We find clear and abundant occurrences of a seismic phase that indicates the presence of melt, some of it observed as far as 28 km from the ridge. The distribution of melt is consistent with discontinuous delivery of melt from the mantle in large volumes, estimated to be on the order of 1 km3. Between 10 and 30 km away from the ridge axis, the areal coverage of the base of the crust by melt is estimated to be at least 10% and may be as great as 20%. A simple statistical model indicates that the melt bodies may be well over 100 meters thick, and they may persist as melt intrusions for thousands of years. These results contradict models of continuous melt transport through the mantle. The wide

zone of melt delivery requires that the oceanic crust thicken with age, contrary to the common assumption that the basaltic crust is almost completely formed within a few km of the ridge. This incorrect assumption stems from the misinterpretation of previously acquired near-axis multichannel seismic (MCS) data. We propose that our observations and the MCS data are consistent with the presence of a permeable reservoir of basaltic melt in an ultramafic matrix that continuously releases melt to form the lower basaltic crust. Ponding of excess melt at the top of this reservoir creates a shallow axial magma chamber that is the source of basaltic dikes and extrusives.

GUEST PRESENTATION:

THE RELATIONSHIP BETWEEN TOPOGRAPHY AND GRAVITY ON EARTH AND VENUS

Dan Peter McKenzie
Professor of Earth Sciences
Institute of Theoretical Geophysics
Bullard Laboratories, Cambridge University

The Magellan project to map the surface of Venus has been outstandingly successful, and has produced spectacular synthetic aperture radar images of almost the whole planet. We now have better knowledge of the topography and gravity of Venus than we do of Earth. For the first time it is possible to do comparative planetology between the two bodies, to test how well our models for geological processes work on another planet. Such a comparison has already produced a number of surprises. Perhaps the most important difference between the two planets is that the surface features of Venus are much more closely related to the convective circulation in the planet's interior than is the case for Earth. The measurement of the admittance between the topography and gravity of a planet as a function of wavelength provides the best way of studying such questions. At long wavelengths the admittance is best determined in the frequency domain, using gravity as input and topography as output. This procedure is used to estimate the admittance in the Pacific and Indian Oceans. The observed values are reduced by volcanism above plumes, which produces a contribution to the long wavelength compensated topography. When this effect is taken into account there is little evidence that the admittance is reduced by the presence of a low viscosity zone in the upper mantle. A similar study of Venus shows an excellent correlation between gravity g and topography h for wavelengths greater than 700 km, with an admittance of about 50 milligals/km. This value agrees well with that expected from numerical axisymmetric models of plumes, and can be used to construct maps of residual topography by calculating h-g/50, where h is in km and g in milligals. Of the major topographic features, only Aphrodite and Ishtar Terrae behave differently, with a value of admittance of about one third of other large structures. By analogy with similar structures on Earth, both are likely to be supported by volcanically thickened crust on top of rising plumes, though the observed relationships do not rule out other models.

POSTER SESSIONS

EFFICIENT KIRCHHOFF MIGRATION IN THE PLANE WAVE DOMAIN

Faruq E. Akbar, Mrinal K. Sen, and Paul L. Stoffa

We describe a method of prestack depth migration in the plane wave (tau-p) domain. The method is based on the Kirchhoff Helmholtz formulation for wavefield propagation. The source and receiver wavefield can be expanded in terms of plane waves. The interaction of the source and the receiver wavefields with a material discontinuity can be expressed by a surface integral over the discontinuous surface. The source travel times are synthesized from the plane wave travel times and the receiver travel times are expressed in terms of plane wave travel times. The plane wave travel times are computed at each grid point of the model using a finite difference approximation of the Eikonal equation with proper boundary conditions. We present our migration algorithm and its implementation on a parallel machine.

The input to the algorithm is the tau-p transformed data recorded by a number of receivers. Each constant-p section can be migrated separately. The summation of all constant-p migrated sections is the final image. Thus, the method is ideal for implementation on parallel computer architectures. We implemented the parallel migration algorithm using PVM (parallel virtual machine) to simulate parallel machine. We also present a scheme to construct source travel times from plane wave travel times. With this scheme we can generate a large number of source travel times using only a few plane wave travel times. With this scheme our method becomes very efficient in terms of computation time without losing accuracy.

STRATIGRAPHY AND STRUCTURE OF A LATE CRETACEOUS STARVED PASSIVE CONTINENTAL MARGIN, SOUTHEAST AUSTRALIA.

Saif M. Alabri and Millard F. Coffin

Multichannel seismic, gravity, and magnetic data from the southeastern Australian margin between 34° and 39°S reveal its detailed structure and stratigraphy. The margin is characterized by a narrow shelf, steep slope and deep abyssal plain with a poorly developed continental rise. The acoustic basement of the shelf is a strong, high amplitude reflector of Paleozoic or early Mesozoic age. It displays erosional relief and is intruded by strongly magnetized rocks, possibly related to coastal Tertiary mafic magmatism. The shelf sediment is built on acoustic basement and thickens southward where progradational seismic sequences are better developed. Sequence stratigraphic analysis reveals mounded reflection facies on the shelf edge, north of ~36.5°S, that appear to be paleo-reef mounds or carbonate buildups. An unconformity above the carbonates suggests termination of reef growth as sea-level dropped. Mid-slope half-grabens and grabens are bounded by normal faults, and in places are filled with sediment. In general, mid-slope structures with central deeps strike parallel to the margin, and their locations appear to intersect the landward extensions of some Tasman Sea fracture zones. Oceanic basement beneath abyssal plain sediment is late Cretaceous to Paleocene in age and is characterized by rough surfaces with mounded structures, easterly-dipping normal faults, and westerly-dipping thrust faults. Abyssal plain sequence stratigraphy consists of transparent, chaotic, discontinuous, and continuous reflection patterns reflecting lateral and

vertical changes of facies. Numerous erosional surfaces may be related to the onset of vigorous oceanic currents in the Paleocene.

Pore Fluid Pressure Variations Along the Decollement Thrust Inferred from 3-D Seismic Reflection Data from the Northern Barbados Ridge

Nathan L. Bangs, Thomas H. Shipley, Paul L. Stoffa

The amplitude and waveform of the seismic reflection from the decollement thrust is examined using 3-D seismic data covering a 25 x 5 km area of the toe of the northern Barbados Ridge accretionary complex to reveal details of the fault zone characteristics. Throughout the survey area the decollement develops high amplitudes, approximately 1/3 that of the seafloor. The amplitudes exceed that of the stratigraphic horizons within the underthrust section beneath the decollement, and that of the horizon seaward of the complex along which the decollement develops; therefore, high decollement amplitudes are believed to be unrelated to inherent sediment properties along the thrust. The pattern of decollement amplitudes correlates poorly with seafloor structure and seismic modeling confirms that little of the high amplitude pattern is caused by focusing effects from the overlying seafloor. The decollement reflection polarity is usually opposite that of the seafloor. Models of the reflection require a decrease in the seismic velocity and density within the fault zone to produce a reflection of similar polarity. These anomalous properties are believed to indicate high porosities maintained by overpressured fluids along the decollement, and detailed variations in waveform and amplitude are thought to reflect the distribution of fluid pressures along the fault.

Seismic models of the decollement reflection simulate two distinct waveforms. Along two ~1 km segments of the fault the reflection is modeled as a 12-m-thick layer in which the velocity is 150 m/s lower within the layer than above or below it. This may be explained by high fluid pressures causing hydrofracturing and dilation within a confined, 12-m-thick interval. A second distinct waveform is modeled as a single interface beneath which the velocity decreases by as much as 200 m/s, with no reflection from a deeper interface related to the base of a thin layer. Here high fluid pressure may dilate an interval thicker than 12 m. Any drop in the fluid pressure with depth probably occurs gradually since a basal seismic reflection is not produced. The single interface is more common throughout the survey area. The 12-m layer appears to develop where the decollement reflection is unusually bright, and may correlate to a segment of the fault where it has stepped down and is reforming, cutting through the underthrust sediment section to a deeper stratigraphic level.

Tectonic Evolution of Bransfield Strait, Antarctica: Intracrustal Diapirism, Distributed Extension and Stratigraphic Response to Marginal Basin Rifting

Daniel H. N. Barker and James A. Austin, Jr.

We present results of analysis and interpretation of multichannel seismic (MCS) profiles from Bransfield Strait, Antarctica. Over 2000 km of MCS data were acquired by the University of Texas Institute for Geophysics (UTIG) and Lamont-Doherty Earth Observatory (LDEO) on R/V Maurice Ewing cruise 91-01 in February 1991. The acquisition utilized a 20 gun array (total: 8385 cu. in.) with a 120 channel/3.25 km streamer. Migrated 30-fold stack sections from within Bransfield Strait are shown here.

Bransfield Strait is a northeast-southwest trending basin located at the northern end of the Pacific margin of the Antarctic Peninsula, between the South Shetland Islands and the Peninsula. The Strait has an asymmetric profile, with a steep northwest margin (South Shetland Islands) and a gentle southeast margin (Antarctic Peninsula). Along the rift axis itself is a zone of neovolcanic constructions connecting the volcanic islands of Deception Island and Bridgeman Island, at the southwest and northeast ends of Bransfield Strait, respectively.

Several important features have emerged from the EW91-01 MCS data. Active normal faulting is seen throughout the basin, indicating ongoing extension. The Antarctic

Peninsula margin is complexly faulted, with the preferred polarity of the normal faults reversing from one dip profile to the next along basin strike. Some fault polarity reversals also occur along individual dip profiles. Normal faults dip inwards toward a common central point, with the inner faults progressively cutting smaller and smaller central fault blocks. In several instances, these faults dip towards high-amplitude, low-frequency reflection events which seemingly form a base to the observed structures. The proximity of these features to the known active volcanism along the rift axis strongly suggests that the high amplitude reflections originate from some kind of magmatic intrusion. Furthermore, these fault features align along a trend ~5° divergent from the trend of the neovolcanic zone, but merge with it towards the southwest. By analogy with observed structures associated with sedimentary diapirism and modeling of such diapirism, we speculate that these aligned features are the product of magmatic diapirism associated with basin extension (Barker and Austin, 1994, Geology, v. 22, p. 657-660). Their presence indicates that extension is not focused at a "spreading center" (the known neovolcanic zone), but instead is distributed across the basin. The divergent trends may further indicate a temporal evolution of the stress regime in Bransfield Strait.

Acoustic basement in Bransfield Strait has been mapped. In general, interpreted rift structures appear to widen and deepen to the northeast. Interpreted continental basement beneath the Antarctic Peninsula descends rapidly beneath syn-rift sediments by normal faulting. This occurs on the South Shetland margin, too, accommodated by fewer large-offset faults. The axial part of the Strait is characterized by inferred neovolcanic constructions, which create an acoustic basement often exposed at the seafloor along the rift axis. Flat-lying sediments along the deep axial part of the basin often appear to be intercalated with these neovolcanics. This intercalation may involve several generations of sills from the neovolcanic center intruded into surrounding sediment, a series of flows at the seafloor which are subsequently overlain by sediments, or a combination of both.

The relationship between the neovolcanic material and inferred continental basement to either side is not yet clear. The basin could be extending such that volcanic material is passively rising at the rift axis, intruding sills into preexisting crust, suggesting onset of oceanic crust formation at an incipient spreading center. Alternatively, volcanic material may be extruding onto preexisting continental(?) crust everywhere, loading and flexing that crust. Because neovolcanic material appears more voluminous to the northeast, a northeast-to-southwest progression of rifting seems likely. Perhaps both the alignment of inferred diapiric intrusions in Bransfield Strait and the apparent sequential opening of the basin are the result of changes in the fundamental mechanism driving extension in Bransfield Strait. Subduction (and hence slab rollback) at the South Shetland Trench could be waning, while to the northeast a significant change in geometry and tectonics is apparently underway at the Scotia-Antarctic plate boundary, resulting in transtensional stresses at the northeastern end of Bransfield Strait (Fig. 9; Klepeis and Lawver, 1992, Eos Transactions, v. 73, p. 563).

The Peninsula margin sediment wedge clearly preserves its progradational character in the upper section. An isochron map of total sediment thickness shows that sediment is thickest where normal faulting thickens the syn-rift section and prograded sediment forms the outer shelf above. Sediment thins both on the inner shelf (probably as a result of glacial erosion) and towards the neovolcanic zone. Unconformities are recognized in the sedimentary section, and intervening sequences are being mapped. These sequences, by their geographical distribution in the basin, may show a time transgression mimicking the suggested time-transgressive basin opening.

Future work in Bransfield Strait includes the integration of magnetics and gravity modeling with the structural interpretation of the MCS data. The interpretation of offshore trench and "fore-arc" MCS profiles will also be tied to the Bransfield Strait interpretation, to look for evidence that geological processes at the trench (e.g., fracture zone subduction) are manifested in the "back-arc" structure.

CENOZOIC BASIN FORMATION IN SOUTHEAST ASIA

Lila Beckley, Lawrence A. Lawver, and Tung-Yi Lee

Several interesting trends can be identified in the pattern of sedimentary basin formation across Southeast Asia. Prior to the middle Eocene, basin formation appears to be restricted to the Indochina and South China margins. At 50 Ma, basin development starts southeast of Kalimantan. It is not until the middle Eocene to Oligocene, though, that basin formation occurs on a regional scale. During this time period, a number of basins form near the major Southeast Asian plate boundaries, including the Sumatran area, Gulf of Thailand and north and east of Kalimantan. Between 44 Ma-20 Ma, the Mergui Basin, the Gulf of Thailand basins, and basins in central Thailand, resulted from the hard collision of Greater India with Eurasia.

Regionally, no major changes in basin history occur from Oligocene until the middle to late Miocene, when the main phase of extension and sediment accumulation ends in a number of basins, particularly in the eastern part of Sumatra, the Gulf of Thailand and near the margin of Indochina. The latest major episode of basin formation occurs near Timor, between 4 Ma and Present, caused by the collision of the Australia-New Guinea plate with the Banda Arc. It is not readily apparent why extensional basins form during periods of collision unless the collision is off-axis and results in extrusion as the collision of India with Eurasia did.

A subregional pattern of basin opening can be identified in the outer-arc basins associated with the Java Trench. The opening of these basins appears to progress from the north (Sibolga and Nias Basins, 30 Ma) to southeast (Timor Basin, 0 Ma).

The progression of basin opening in the eastern Sumatra and Java areas is not as clear. During the middle Eocene, the Sunda Basin formed then the Mergui, North Sumatra, Central Sumatra and South Sumatra basins formed in the Oligocene. The inclusion of sedimentary basins on paleoreconstructions of Southeast Asia highlights the complexity of the tectonic history of the region.

VELOCITY ESTIMATION AND NMO CORRECTION USING NEURAL NETWORKS

Carlos Calderon

A feedforward neural network (NN) is used to predict seismic velocities for a 1-D earth from seismic data by training a network with several velocity models and then using the trained network to derive velocities at distinct surface locations. In this approach, seismic traces from CMP gathers are input to a NN, and the output neurons represent velocity models that are used to NMO correct the data. After training, the NN will be used as an interpolator thereby avoiding the need to estimate velocities at every CMP location along a seismic line. A nonlinear optimization procedure is used to obtain the velocity models. The objective function for the optimization is defined by the difference between a partial stack of traces with all the traces after NMO correction. The seismograms will be corrected properly when they match the partial stack of traces.

2-D RESISTIVITY INVERSION USING SPLINE PARAMETERIZATION AND SIMULATED ANNEALING

Raghu K. Chunduru Mrinal K. Sen, and Paul L. Stoffa

Successful inversion of geophysical data depends on the prior information, proper choice of inversion scheme and on effective parameterization of the model space such that the model representation is appropriate and efficient. Inversion of resistivity data has long been recognized as a nonlinear or quasi-linear problem. Traditionally 2-D resistivity inversion has been performed by trial and error methods and with linear and iterative linear methods. The linear and iterative linear methods are limited because of the requirement of good prior knowledge of the subsurface. Unlike linear and iterative linear methods the nonlinear inversion scheme does not depend on starting solution, but prior information helps to reduce the computational cost and obtain geologically meaningful results. In the present study we have applied a nonlinear optimization scheme called very fast simulated annealing (VFSA) in the inversion of 2-D dipole-dipole resistivity

data, to image the subsurface. Unlike Metropolis simulated annealing (SA) in which each new model is drawn from a uniform distribution, VFSA draws a model from a Cauchy–like distribution, which is also a function of a control parameter called temperature. The advantage of using such a scheme is that at high temperatures, the algorithm allows for searches far beyond the current position, while at low temperatures, it looks for improvement in the close vicinity of the current model. We have used the mean square error between the synthetics and original data as the error function to be minimized. The synthetic response for 2-D models were obtained by finite difference modeling and cubic splines were used to parameterize the model space to get smooth images of the subsurface and to reduce computational cost. VFSA was used to estimate the conductivity at the spline node locations. The inversion was applied to various synthetic data to study the influence of starting solution, and the location of the spline nodes. Finally we applied it to real data collected over a disseminated sulfide zone at Safford, Arizona and compared the results with those obtained from a linearized inversion and a model based on geologic and well log data. The VFSA results are in good agreement with the previously published results.

TECTONICS OF THE MACQUARIE RIDGE COMPLEX

Millard Coffin, Cliff Frohlich, Paul Mann, Chris Massell, and Laurie Schuur

The University of Texas at Austin Institute for Geophysics

The Macquarie Ridge Complex forms the boundary between the Pacific and Australian plates south of the Alpine fault of New Zealand. It has been proposed to be a transpressional strike-slip fault zone that is evolving into a nascent subduction zone. In early 1994, we surveyed ~150,000 km2 of the plate boundary aboard R/V Rig Seican sonar and bathymetry, 8- and 96-channel seismic reflection, gravity, and magnetic data. The initial results of the cruise, based primarily on interpretation of sidescan and bathymetric images, include: 1) An active zone of deformation a few tens of km wide is defined by asymptotically merging Cenozoic fracture zones on the Australian and Pacific plates. This "Macquarie fault zone" typically occupies the Macquarie Ridge Complex's crest or flanks. The Macquarie fault zone's continuity, linear fabric, shallow seismicity corresponding with mainly right-lateral focal mechanisms, and colinearity with the Alpine fault zone suggest active right-lateral strike-slip motion; 2) Relocation of the major 1989 earthquake places its epicenter and error ellipse on the narrow ridge. This 200 km long, seismogenic fault rupture may correspond precisely with the Macquarie fault zone; MR1 mosaics show no other faults or fracture zones of sufficient length or proper orientation to generate such a large earthquake; 3) Preliminary restoration of fracture zone morphology yields ~450 km of right-lateral offset along the Macquarie Ridge Complex, consistent with ~480 km of offset documented along the Alpine fault; 4) Dredges suggest that the Macquarie Ridge Complex is mainly composed of oceanic basalt. Serpentinite, peridotite, and gabbro on Macquarie Island and in some dredges suggest part of the Macquarie Ridge Complex may obducted mantle and lower oceanic crust; 5) Some thrusting is observed in young sediment deposited in deeps adjacent to the Macquarie Ridge Complex.

SEDIMENTARY EVOLUTION OF THE INDIAN OCEAN

Thomas A. Davies

The breakup of Gondwana in the Late Jurassic, followed by the dispersal of the Southern continents, created a series of new ocean basins and destroyed large parts of the equatorial Tethys ocean. The effects of this tectonic evolution on ocean circulation, climate, and continental erosion are reflected in the sedimentary record of the Indian Ocean, which has been sampled by drilling at more than 100 DSDP and ODP sites.

Changes in wind and surface water circulation patterns are shown by the distribution of volcanogenic sediments. The opening Indian Ocean experienced a change from westerly surface currents, generated by high latitude westerly winds, during the Mesozoic to gyral circulation in the Cenozoic. Since the development of the monsoon system in the late Miocene, the northwestern Indian Ocean has also experienced seasonal reversal of winds and surface circulation.

Deep water circulation patterns are revealed by the distribution of areas of potential hiatus development (APHiDs), recognised from the distribution of sites in hiatus and the associated distribution of unconformity upper boundaries (terminations). APHiDs formed along flow paths of proto-Antarctic Bottom Water and Intermediate waters. Expansion and contraction of APHiDs indicate changes in the volume of these water masses. Since the late Oligocene, the proto-Antarctic Bottom Water flow has decreased during intervals of increased glacial intensity, whereas the proto-Antarctic Intermediate Water increased in volume during these periods. (This contrasts with interpretations made by other workers.)

Changes in terrestrial erosion patterns and rates are recorded in the development of deep-sea fans along the eastern margin of Africa (Zambesi fan, western Somali basin) and east and west of India (Indus and Bengal fans, respectively), with the principal locus of terrigenous input progressing clockwise through time from the Zambesi fan (late Oligocene/early Miocene) to the Bengal fan (late Miocene/Plio-Pleistocene).

TECTONIC STRUCTURE OF THE KERGUELEN PLATEAU, SOUTHERN INDIAN OCEAN, BASED ON SATELLITE-DERIVED GRAVITY AND SEISMIC REFLECTION DATA

Lis K Könnecke and Millard F Coffin

The Kerguelen Plateau, in the Southern Indian Ocean, is a giant mafic igneous province. Tectonic studies of the plateau had been limited to sparse shipboard data until the recent release of high resolution satellite altimetry data, which reveal numerous structural elements suggesting a complex geologic history. In this study we integrate Geosat and seismic reflection data to elucidate the tectonic history of the Kerguelen Plateau from Early Cretaceous to Eocene time.

While our overall understanding of subdividing the Kerguelen Plateau province into four major tectonic sectors - a northern (NKP), a southern (SKP), the Labuan Basin, and Elan Bank - has been largely confirmed, each of these sectors display structures more complex than previously assumed. Three major tectonic trends can be observed: NW-SE, E-W, and N-S. The predominant NW-SE trend is found on all scales. It includes a well-defined graben on the central SKP (Central SKP Graben) and a chain of gravity highs, interpreted as volcanic centers, linking the Kerguelen Archipelago, on the NKP, with Heard Island. E-W trends dominate Elan Bank, as well as an elongated gravity low on the central SKP (59°S Trough), while the 77°E Graben on the northern SKP trends N-S.

The general structural pattern of the Kerguelen Plateau reflects the NW-SE breakup fault pattern between Kerguelen and Broken Ridge. The N-S and E-W trends on the SKP and Elan Bank are less clearly related to Cenozoic plate motions. They could be associated with N-S trending Late Cretaceous and Early Tertiary fracture zones in the Wharton Basin, or to a relict ridge-transform system NW of the NKP. We hypothesize that the linear features on the SKP formed prior to the establishment of the current Southeast Indian Ridge system in Eocene time. A pattern of low angle normal faults suggest that the Central SKP Graben is extensional, while complex faulting, including flower structures, indicate significant strike-slip components for the 77°E Graben and 59°S Trough.

QUANTITATIVE TECTONIC RECONSTRUCTION OF THE DIACHRONOUS COLLISION OF THE ONTONG JAVA PLATEAU ALONG THE 3000 KM LENGTH OF THE NORTHERN MELANESIAN-SOLOMON-NEW IRELAND CONVERGENT MARGIN

Paul Mann and Lisa Gahagan

The Ontong Java Plateau (OJP) of the southwest Pacific is the size of the Iberian Peninsula and has a crustal thickness up to 40 km. OJP formed as an oceanic plateau of perhaps much larger dimensions in Aptian time and would behave as a continent upon entering subduction zones. Falvey, Auzende and others have outlined qualitative models for the contact of OJP with a N and NE-facing Northern Melanesian arc during Miocene time. The inability of the subduction zone to consume the plateau resulted in arc flipping and opening of the present area of the North Fiji Plateau as a result of W to SW migration of a

more recent SW- and W-facing Vanuatu arc. We present a quantitative reconstruction using UTIG PLATES 2.0 software of the position of the OJP from the time of assumed contact 15 m.y.b.p. and reversal at the eastern tip of the Northern Melanesian Borderlands to present-day active arc collision/reversal beneath the Solomon and New Ireland margins.

Assumptions of the model include: 1) OJP remains fixed to the Pacific plate; 2) Pacific-Australia relative motion is known from the Pacific-Antarctica-Australia circuit; OJP motion relative to the arc is steadily to the west-southwest at 254; the Solomon-Northern Melanesian arc is continuous, straight, and strikes 305; 4) opening of the North Fiji Plateau occurs at 8 m.y. in a direction of 45; and 5) the OJP is completely subducted at an angle of about 36° based on the dip of the seismic slab beneath the Solomon arc.

Implications of the model include: 1) half of the OJP may have disappeared beneath the Northern Melanesian-Solomon-New Ireland island arc; the amount of OJP basement and pelagic sedimentary cap offscraped at the Vitiaz-North Solomon-Kilinailau trenches remains unknown; 2) the southern extension of the OJP is predicted to lie beneath and perhaps elevate the North Fiji Plateau; 3) the style of rapid arc migration and back-arc spreading that occurred following reversal in the Vanuatu arc-North Fiji Plateau is retarded in the Solomon arc by thicker-than-normal crust of the Pocklington Rise and Woodlark spreading center; and 4) WSW convergence between the OJP and continental crust in New Guinea has resulted in sideways, suture-parallel "tectonic escape" of the New Britain arc over young ocean floor of the Solomon Sea.

Jurassic Reconstruction of the Gulf Of Mexico Based on Combined Geophysical and Geological Data

Gyorgy Marton

The Jurassic evolution of the Gulf of Mexico basin is intimately related to the breakup of the late Paleozoic supercontinent Pangea and to the early evolution of the Atlantic/proto-Caribbean system. General consensus, however, has not been achieved as t many of the important details of this undoubtedly complicated breakup event.

The presented model is constrained by a refined oceanic crust definition in the Gulf of Mexico and by the known kinematic framework of the large continental blocks (North America plate, Afro-South America plate). The refined definition of the oceanic are in the Gulf of Mexico was obtained by combining the results of different geophysical data sets, including: a) refraction data, b) magnetic data, c) depth to the basement map of the Gulf of Mexico, d) multichannel seismic data in the eastern Gulf of Mexico area, and e) gravity data. Reconstruction of the basin was completed using Plates 2.0 plate reconstruction software to visualize the movement of the Afro-South America plate and the Yucatan, Florida-Bahamas microplates during the Mesozoic breakup .

During the Late Triassic? to late Middle Jurassic syn-rift stage the relatively stable Yucatan block translated southeastward along a major transform zone in eastern Mexico. This motion accommodated a large amount of extension in the area of the future gulf. At the same time the Florida/Bahamas block extended in a similar direction which formed a series of basins along the present day west Florida shelf. Contrary to many published Gulf of Mexico evolution schemes, the presented model does not require major strike-slip faulting between Yucatan and Florida. However, activity along a major shear zone in the eastern Gulf (the Bahamas Fracture Zone and its northeastward extension) is postulated. Another important shear zone separated the zone of extension in the Gulf of Mexico from an Andean type arc Mexico. Rock evidence from the rim of the basin indicate that throughout the rifting phase the basin was emergent, an area of erosion, localized continental sedimentation and volcanism.

A rotation pole for the Yucatan block in the southeastern Gulf of Mexico (23.46N, 84.74W) is proposed for the late Middle Jurassic (Callovian) to earliest Cretaceous (Berriasian) drifting stage. Around this pole the Yucatan block rotated about 42 degrees counterclockwise out from the northern Gulf to accommodate the newly formed oceanic crust in the basin. Reconstruction of the

Louann and Campeche salt provinces shows that some of the original salt may had been deposited in an already partially opened oceanic basin in Callovian to early Oxfordian time. The drifting stage was characterized by cessation of continental margin volcanism, major transgression and basinwide marine sedimentation.

The kinematic framework for the Gulf of Mexico opening implies that major rifting in the southeastern Gulf of Mexico occurred during the Late Jurassic drifting phase as the Yucatan block rotated counterclockwise relative to the Florida/Bahamas region. Seismic data clearly indicate that in the southeastern Gulf of Mexico rift system a northward increasing amount of extension had been accommodated, supporting a southward propagating rift model for this area. Rifting in the southeastern Gulf ceased by late Berriasian time, giving an estimate for the completion of oceanic crust formation in the Gulf of Mexico.

Fluid Pathways and Deformation in the Costa Rica Accretionary Prism

Kirk McIntosh

Fluid pressure and fluid pathways are intimately tied to deformation and structural development in accretionary prisms. Using a 3 dimensional volume of seismic reflection data, we have identified active structural processes of the NW Costa Rica convergent margin and interpreted likely fluid pathways associated with these processes. Our preliminary analysis indicates that most faults in this area are structurally active only temporarily during which time they may also serve as fluid pathways. In contrast, the basal detachment and a few larger out-of-sequence thrust faults appear to be more continuously active. The Costa Rica accretionary prism contains few, if any, rock bodies that are large enough to produce seismically resolvable stratal reflections, therefore the reflections that are visible within the prism are interpreted largely as fault plane reflections. To identify the active faults, and presumably the active fluid pathways, we have examined reflection amplitude, polarity, and continuity. An additional characteristic that we used to evaluate the activity of many faults is whether they extended through the prism to the seafloor. This is especially important because these faults can be examined directly during submersible dives and associated fluids may also be identified and sampled. The amplitude variation of the seafloor reflection correlates inversely with dip, so it is a particularly good way to identify fault outcrops when displayed in map view. We used this display combined with the vertical seismic sections to identify the most likely zones of active faulting and fluid venting. On subsequent submersible dives we detected numerous fault scarps and associated vents where the surface reflection features bands of low amplitude.

Additional work is in progress to model the waveform of selected fault plane reflections. In particular we hope to identify whether the reversed polarity decollement reflection near the trench results from thrust related velocity inversion or if the fault consists of a discrete low impedance zone related to overpressured fluids. During the recent submersible program no fluid vents were identified where this reflection approaches the seafloor.

Investigation Of Non-Double-Couple Earthquake Sources

Paul A. Nyffenegger, Lian-She Zhao, and Cliff Frohlich

The Harvard group now routinely determines earthquake moment tensors for many earthquakes of ~Mw 4.8 and larger, however, for some the radiation cannot be explained solely as being due to slip along a simple planar fault. We examine the nature of non-double-couple (NDC) sources by investigating earthquakes in groups; for each well determined NDC event we find nearby well determined double-couple (DC) earthquakes and jointly study the events to eliminate errors attributable to earth structure. We organize this investigation into two stages: a) Comparison and modeling of seismograms; and b) Modeling of the source mechanisms.

The comparison and modeling of the NDC and DC waveforms is mainly observational. We compare the broadband displacement waveforms with ray theory synthetics to determine whether NDC events are more likely than DC events to possess distinct, identifiable

subevents. We also band pass filter the records into long period (0.006-0.02 Hz), mid-period (0.02-1. Hz), and short period (1.-4. Hz) frequency bands for comparison. In the future we also intend to use as much of the bodywave train as possible in the comparisons, including phases such as ScP and PKP. From this analysis we hope to determine what fractions of NDC and DC sources possess identifiable subevents, and whether this depends on event size and focal depth. Currently we are automating the comparison procedure using a group of events from the Tonga region. The NDC event in this group is complex, with distinct subevents.

We use a grid search method to redetermine source mechanisms using both teleseismic and regional waveforms where available. The NDC source is determined as a sum of a major DC and a minor DC having the same three principal axes, but with the T and B, or P and B axes exchanged. The grid search method determines the strike, dip, and rake for the major DC and the strength of the minor DC that best fits the waveform and first motion data. Where regional waveform data is available, we relocate the event prior to final determination of the source parameters by searching for the location most consistent with waveforms from individual stations. We performed initial tests of our method using regional waveforms from shallow reported NDC earthquakes occurring on 17 Aug. 1991, 26 Apr. 1992, and 15 Sept. 1992 in California. Our preliminary results indicate a much smaller non-double couple component than reported by Harvard, and also a somewhat different hypocentral location.

The most likely explanation for these NDC sources is that they are caused when two or more subevents with different focal mechanisms occur nearly simultaneously. However, systematic errors in the source determination process may also cause large apparent NDC components. Understanding the complex NDC earthquakes is of importance because they may elucidate the fundamental mechanics of the earthquake process. Furthermore, small magnitude ($Mw < 5.0$) NDC earthquakes might be mistaken for seismic events of human origin. Finally, understanding the nature of systematic errors afflicting source determination helps to reduce erroneous identification of natural and manmade seismic events.

SAMPLING BASED APPROACHES TO ESTIMATING UNCERTAINTIES IN GEOPHYSICAL INVERSION

Mrinal K. Sen
The University of Texas at Austin Institute for Geophysics

The Bayes or the Tarantola-Vallette formulation of geophysical inverse problem describes the solution of the inverse problem as the a posteriori probability density (PPD) function in model space. Since the complete description of the PPD is impossible in the highly multidimensional model space for geophysical applications, several measures such as the highest posterior density (HPD) regions, marginal PPD and several orders of moments are often used to describe the solutions. Calculation of such quantities requires evaluation of multidimensional integrals. A faster alternative to enumeration and blind Monte-Carlo integration is importance sampling which may be useful in several applications. Importance sampling can be carried out most efficiently by a Gibbs sampler (GS). We introduce here a new method called parallel Gibbs sampler (PGS) based on genetic algorithms (GA) and show that the results from the two samplers are nearly identical.

Several nonlinear optimization methods based on simulated annealing (SA), GA and some of their variants can be devised which can be made to reach very close to the maximum of the PPD. Such maximum a posteriori (MAP) estimation algorithms also sample different points in the model space. By repeating these MAP inversions several times, it is possible to adequately sample the most significant portion(s) of the PPD and all these models can be used to construct the marginal PPD, mean, covariance etc. We illustrate these by numerical examples from two geophysical inversion problems, namely the seismic waveform inversion and the inversion of resistivity sounding data. Our numerical results show that the marginal PPD's, mean and covariance obtained by these approximate methods agree very well with those evaluated by GS and the PGS. They are, however, computationally faster than the more exact methods. The GS and the PGS require nearly the same number of function evaluations for convergence. The PGS, however, is ideally suited for parallel computation. We also show the estimated posterior marginal density functions and

covariances of compressional wave velocity, impedance and Poisson ratio of an earth model, derived from a plane wave transformed common mid point data collected at the Carolina trough off the east coast of the United States.

SEISMIC PROCESSING USING PVM: PRESTACK 3D KIRCHHOFF MIGRATION AND MODELING

Vikramaditya Sen, Mrinal K. Sen, and Paul L. Stoffa

In this paper, we report on the PVM based implementation of seismic modeling and a traditional prestack Kirchhoff migration for arbitrary models of the Earth varying in three dimensions. Kirchoff migration treats a reflector of seismic energy as a surface made up of a large number of point scatterers and attempts to estimate the 'strength' of each point scatterer by summing up samples of the reflected energy (measured on the surface of the Earth) that could have come from that point scatterer. This is in fact an implementation of Huygen's principle. We apply our migration scheme on the measurements of each individual receiver in the survey. Alternately, we can also model the seismic response of an earth model varying in three dimensions and compute the arrival times for a given source-receiver geometry. We are using this scheme to migrate ocean-bottom seismometer data collected near Barbados in 1992.

We have been able to sharply reduce our elapsed (computer) times by using a PVM based scheme that works on SUN workstations and Cray-YMP. PVM (Parallel Virtual Machine) is a software environment that enables us to link together several workstations and use the cluster to simulate a parallel computer. We distribute the surface measured seismic data among the various nodes of the virtual machine and we can extract the corresponding partial images at the various nodes after migration. Finally, we use a hypercube collapsing scheme to add up the partial images obtained from the various nodes into the final image. We have made a study of the variation of performance statistics with varying the number of nodes (workstations) in the virtual machine. An approach like ours holds great promise in overcoming some of the tougher demands placed by seismic processing on the computational resources of academic institutions.

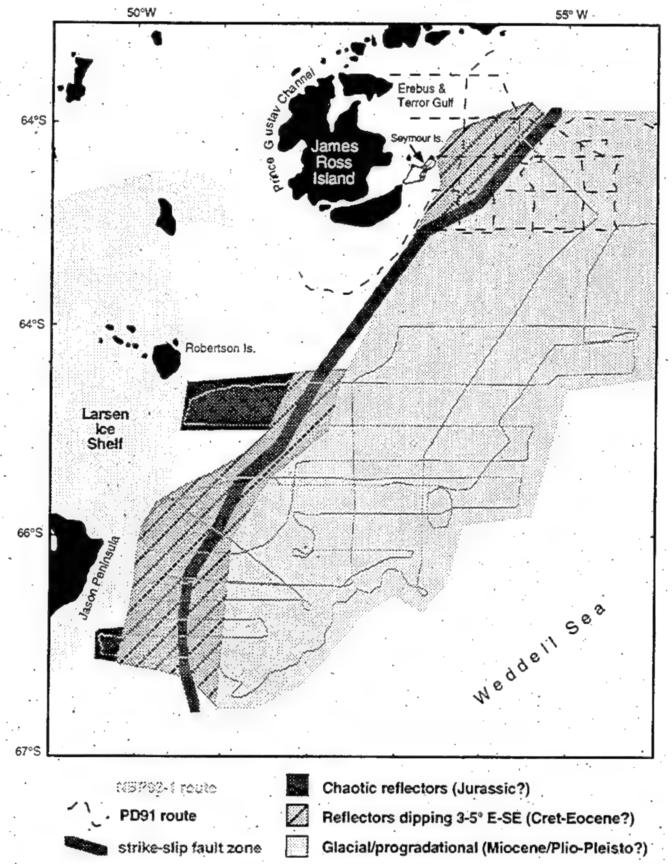
SEISMIC STRATIGRAPHY OF THE LARSEN BASIN, EAST ANTARCTIC PENINSULA

Benjamin J. Sloan and Lawrence A. Lawver; and John B. Anderson (Rice University)

The Larsen Basin lies behind the extensive Palmer Magmatic Arc and has been the focus of considerable onshore geologic investigation. Two marine geophysical cruises surveyed the Antarctic Peninsula continental shelf east of Seymour Island and south to Jason Peninsula, aboard the *R/V Polar Duke* in 1991 and *R/V Nathaniel B. Palmer* in 1993, respectively (Figure 1). Gravity, magnetics, bathymetry, and single-channel seismic data reveal a zone of Mesozoic volcanics succeeded by Cretaceous and Paleogene clastic beds dipping 3-5° east, overlain by Neogene progradational and Plio-Pleistocene aggradational deposits. The post-Eocene section, not preserved onshore, is assumed to have recorded the cooling of peninsular climate and onset of glaciation.

The 1991 survey was conducted east of Seymour Island, and included acquisition of seismic data and piston cores, in an attempt to extend the stratigraphic record documented onshore. Water depths in the area average 300 m, but a trough over 500 m deep extends out of Prince Gustav Channel into the Erebus and Terror Gulf, the apparent result of a grounded ice sheet which scoured and/or depressed the seafloor. The tilted stratigraphic section which has been exposed is an ideal site for shallow drilling of the climatically crucial Oligocene section.

Cruise NBP93-1 ran twelve west-east traverses of the previously uncharted shelf between the Larsen Ice Sheet and Weddell Sea pack ice to nearly 67° south latitude. Echo-soundings revealed two broad west-east oriented troughs, reaching 500 m deep and separated by a ridge which averages 330 m. As with the outer Prince Gustav Channel, these troughs are attributed to erosion by grounded ice bodies. Gravity measurements indicate a north-south trending negative anomaly, centered on the shelf, with a high to the west attributed to shallow, dense acoustic basement, and a strong positive bathymetric edge-effect along the shelf edge.



Generalized geologic map depicting distribution of primary units and fault traversing the study area. The fault zone varies along strike from a discrete plane and zone of disruption in the north to multiple discrete offsets in the southern area. Age, throw, and origin of the fault are unknown, but it does appear to offset a seabottom reflector on line LS93-00. The distribution of units three and four is coincident as the Plio-Pleistocene sits atop the Mio-Pliocene prograding units.

Single-channel seismic data indicate a section, in both areas, broadly divisible into four units (Figure 1). The western edge of the basin returned chaotic reflections, particularly near Robertson Island and Jason Peninsula, indicative of acoustic basement which may be Jurassic arc-related volcanics, a hypothesis consistent with positive gravity and magnetic anomalies. The zone passes unconformably into a unit composed of high-amplitude, continuous reflectors dipping seaward 3 to 5°. These are truncated at the sea bed, presumably by glacial erosion. Several prominent surfaces of basinward shift in coastal onlap are identifiable within this unit and are correlatable between dip sections; they are possibly equivalent to those described on James Ross Island by Pirrie and Crame. Correlative dipping layers on Seymour Island are Late Cretaceous to Paleogene in age and were tilted during the late Paleocene. Near-vertical faults in a margin-parallel (northeast trending) zone offset reflectors, in places exhibiting flower structures characteristic of strike-slip displacement. Because the faults extend upward to a seabed erosion surface, it is not possible to estimate an upper limit to its age. The tectonic regime to which this style of faulting may be attributed is not known.

An angular unconformity separates the dipping reflectors from the third unit, which is progradational. Sediments were apparently derived from the James Ross Island vicinity and from near Joinville Island. These deposits prograde nearly to the present shelf margin and are geometrically comparable to Neogene sequences documented elsewhere, including those from the Ross Sea, and are attributed to waxing and waning of Antarctic ice sheets and sea level fluctuations. Continuous, high-amplitude reflectors mark regional erosional surfaces. Cut-and-fill geometries, including channels over 10 km wide, are ubiquitous in the unit as evidence of subglacial processes.

The youngest unit includes discontinuous, variable-amplitude reflectors and local erosional surfaces up to several kilometers wide in an overall aggradational geometry. Massive, chaotic reflector patterns characterize units interpreted as till tongues. These glacial and glacial-marine deposits are thought to have accumulated under the increasingly fluctuating ice volumes of the Plio-Pleistocene.

INTERMEDIATE-DEPTH (~ 210 KM) EARTHQUAKES IN HINDU KUSH

Fumiko Tajima

The Pamir-Hindu Kush region is located at the northwestern corner of the collision zone between the Indian and Eurasian plates. The seismic activity is high and characterized by diffuse shallow events (0-70 km) and clustered intermediate-depth events which form a steep Wadati-Benioff (W-B) zone down to 300 km in two separate segments beneath Hindu-Kush. The intermediate-depth events show dominantly down-dip tensional stress while the diffuse shallow activity shows varying stress axis orientations. This W-B zone is among a few continental W-B zones worldwide where large intermediate depth earthquakes take place. The physical mechanisms responsible for the occurrence of large intermediate-depth events are not well understood. A fundamental question concerning such activity is how brittle or frictional sliding can occur at such high temperatures and pressures within slabs and what the cause of stress accumulation in this source area is.

This study focuses on the deeper segment of the narrow zone (30 x 50 km) where three large events (Mw = 7.5 in 1965; 7 in 1974; and 7.4 in 1983) took place since the World Wide Standard Seismographic Network has been installed. These events produced substantial aftershocks, which is not typical for intermediate-depth and deep earthquakes. The immediate aftershocks (5.5 < Mw < 6.3) with similar mechanisms to that of the main event are located on a steep plane within the slab and may delineate the fault rupture plane. Seismicity catalogs prior to 1963 indicate that such high activity has been recorded repeatedly since the beginning of this century. Recently we managed to collect seismograms recorded by the Wiechert seismometers at Uppsala station (UPP) in Sweden for more than ten events which took

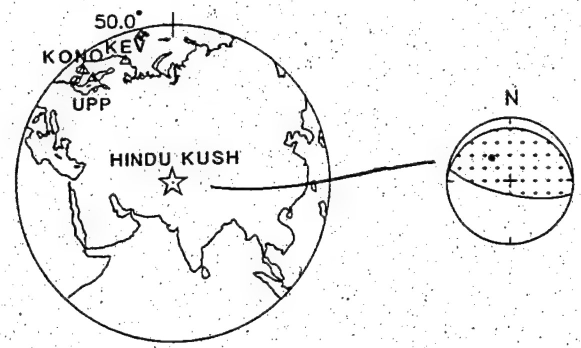


Fig. 1. Large intermediate-depth source area in the Hindu-Kush region and the locations of station UPP, and two modern digital instrument stations, KONO and KEV in a equal area projection map. The focal mechanism for the recent large event in 1983 is also shown.

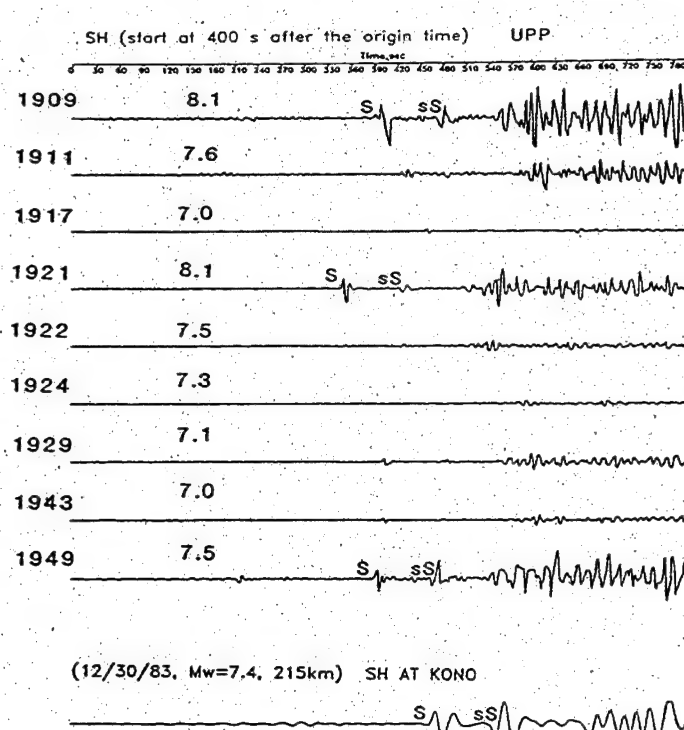


Fig. 2. SH waveforms at UPP for nine events (M > 7) which took place in that source area during the period of 1909 to 1949. The record onset times are lined up at 400 s after the origin times. The bottom trace is the SH wave at KONO for the 1983 earthquake for the use to compare and calibrate the solutions with the historical seismograms. Note that most of the intervals between sS and S are about the same; and this implies that these large events took place at the same hypocentral locations.

place in that source area since 1908 (see Fig. 1 for the source area and the UPP location). The waveforms are impressively clear and clean and the intervals between S and sS phases indicate that these events took place at about the same location (Fig. 2). Note that the variation of S wave arrivals may be due to the errors in the origin times or clock calibration. Three events in 1909, 1921 and 1949 seem to have comparable moment release (note that magnitudes prior to 1963 were overestimated in general). It is our immediate interest to estimate the released moments of these events and possibly the mechanism solutions. We are applying a modern technique to determine the centroid moment tensor solutions using the historical seismograms recorded at the single station (UPP). To calibrate the solutions, we use modern digital network records (e.g., Global Digital Seismographic Network or Global Seismographic Network of IRIS) recorded for recent events from the same area. The modern network includes stations KONO and KEV which are located in a similar distance and azimuth to those of UPP from the source area. This is a collaborative work with Dr. E. A. Okal and his students at Northwestern University.

MECHANISMS FOR RAPID REVERSALS OF VERTICAL MOTION IN THE NEW HEBRIDES AND SOLOMON ARCS RELATED TO COLLIDING FEATURES

Fred W. Taylor, Paul Mann
Martin Lagoe, Andrew Quarles

We present isotopic dates and paleobathymetric evidence that large areas (>500 km2) of the New Hebrides and Solomons island arcs subsided 100's of m, then reversed and uplifted 100's of m, all since ~200 Ka. In both cases, reversing vertical tectonism occurs where major bathymetric features are subducting.

In the central New Hebrides arc, the d'Entrecasteaux ridge, ~100 km wide and standing nearly 5 km above the ocean floor, is underthrusting Espiritu Santo Island. Isotopic dating of reef terraces up to 400 m above sea level (ASL) constrains the following vertical tectonic history: 1) early to mid-Pleistocene uplift, 2) growth of a reef at ~215 Ka (isotope stage 7), 3) subsidence at a mean rate of 4-5 mm/yr, 4) growth of a reef at ~125 Ka (isotope substage 5e), 5) uplift since ~125 Ka at a mean rate of ~3 mm/yr accelerating to a Holocene mean uplift rate of ~6 mm/yr.

In the Solomons arc, the Woodlark spreading system, rising 1500 m above the adjacent Woodlark basin, is underthrusting the 150 km-long New Georgia segment. Isotopic dating and paleobathymetry constrain the following vertical tectonic history: 1) subsidence of the outer forearc region (Tetepare and Rendova Islands) to depths of ~1500 m and deposition of marine turbidites until after 270 Ka, 2) uplift to sea level and erosion of an unconformity, 3) subsidence to ~500 m BSL and deposition of bathyal sediments, and e) uplift above sea level with Holocene uplift rates up to at least 7 mm/yr on Tetepare and Rendova. On the main volcanic arc, barrier reefs formed around the New Georgia and Vangunu Islands as they subsided >300 m. At ~100 Ka, subsidence was replaced by uplift of 10-100 m that accelerated to Holocene rates of ~1 mm/yr on the volcanic arc compared with up to 7 mm/yr on the outer edge of the arc at Tetepare and Rendova.

Mechanisms such as thermal effects due to subduction of spreading ridges, tectonic erosion or underplating, and isostatic adjustments to subducted bathymetric features are not likely to function on the observed time scales. Plate subduction was only about 25 km at Espiritu Santo and 20-30 km at New Georgia since 200 Ka. Uplift of the arc crust by horizontal forces imparted by impingement of bathymetric features is a more likely mechanism for the observed widespread and rapid oscillatory movements. Such a mechanism implies that the arc crust should display large wavelength deformation as suggested by regional variations in reef terrace elevations. Rapid uplift accompanies a phase of strong coupling between the arc and underthrusting features. As a feature is subducted to greater depths, interplate coupling decreases dramatically, horizontal forces relax, and the tectonic bulge collapses until a trailing bathymetric feature impinges and initiates a new cycle of uplift.

MIGRATION VELOCITY ANALYSIS USING 3-D SEISMIC DATA FROM THE NORTHERN BARBADOS RIDGE COMPLEX

Allison C. Teagan, Thomas H. Shipley, Nathan L. Bangs, and Milo M. Backus

A three-dimensional seismic reflection data set acquired in June 1992 imaged a 125 km2 area of the northern Barbados Ridge accretionary prism. We performed a migration velocity analysis to determine a velocity function within subsets of the 3-D volume. Due to the three-dimensional structure within these data, we expect that the optimal migration of the 3-D data volume requires velocities closer to true geologic velocities than the velocities derived from the optimal migration of a 2-D data set. The analysis was conducted from a series of 2-D x 2-D fk migration velocity tests on two 5 km x 5 km data cubes from the seaward section of the survey area. 2-D x 2-D migration consists of two successive 2-D migrations in perpendicular directions and produces results similar to the full 3-D migration with considerably less computation. A set of one-pass, full 3-D finite difference migrations is currently in progress. One data cube is located at the deformation front and is centered around a circular, flat-topped volcanic feature. The sensitivity of velocity in migrating this feature provides a good basis for the velocity interpretation.

We centered the velocity trials around our initial estimate of the best migration velocity, and we included undermigrated and overmigrated extremes. We created movie loops of individual lines extracted from the data cube migrated at the different velocities. Using the movies, we were able to qualitatively determine the best migration velocity based on the focusing of diffractions. We derived velocity functions for two lines from each data cube. The average seafloor to basement interval velocity varies from 1720 m/s to 1940 m/s over a distance of 2.4 km just arcward of the trench axis. This is consistent with other velocity data for the area. A preliminary map of the 3-D velocity field shows there are significant sediment velocity increases related to the initial stages of deformation at the trench.

MIGRATION MISFIT AND REFLECTION TOMOGRAPHY: CRITERIA FOR PRE-STACK MIGRATION VELOCITY ESTIMATION IN LATERALLY VARYING MEDIA

Carlos L. Varela, Paul L. Stoffa, and Mrinal Sen

We compare automatic pre-stack velocity estimation in laterally varying media based on migration misfit and reflection tomography criteria using very fast simulated annealing. The migration misfit estimates are based on the lateral consistency of neighboring depth migrated shot gathers, while the reflection tomography estimates rely on the travel time match between observed and synthetic data via waveform misfit after amplitude equalization. Our results show that the migration misfit estimates have better convergence but lower resolution than estimates based on the reflection tomography criterion. The combination of these two criteria during the inverse process should improve resolution and convergence of background velocity estimates.

CONTROLS ON GLACIAL-MARINE ACCUMULATION RATES IN THE YAKATAGA FORMATION, GULF OF ALASKA

Sarah D. Zellers

Accumulation rates are calculated for the Yakataga Formation, northern Gulf of Alaska, in order to understand the controls on glacial-marine sedimentation along this glaciated active continental margin. Geometries of depositional sequences within the Yakataga Fm. are a function of the complex interplay between sediment supply, eustasy, and tectonics. An increase in accumulation rates through time is documented for the entire formation using data from lowermost Yakataga outcrops at Yakataga Reef and for eight sequences within the offshore Yakataga Fm. Accumulation rates based on present day thicknesses are low (hundreds of m/my) in the lowermost part of the Yakataga, but then increase to several thousands of m/my at 2.5 Ma which corresponds to the onset of regional North Pacific glaciation. Younger offshore Yakataga sequences have accumulation rates from 2000 to more than 6000 m/my. Accumulation rates using decompacted sediment thicknesses derived from

backstripping indicate rates that are up to 1.3 times higher. This increase in accumulation rates is due to a combination of increased subsidence and the intensification of glaciation as uplift of the Chugach and St. Elias Ranges continued through time. Subsidence analyses done using backstripping indicate that sediment loading (up to 6 km) and tectonic subsidence (up to 2 km) are the primary controls on sedimentation along this margin.

APPLICATION OF GENETIC ALGORITHMS TO EARTHQUAKE SOURCE PARAMETER DETERMINATION

Ran Zhou, Fumiko Tajima and Paul L. Stoffa

Determination of major earthquake source parameters is a nonlinear and multidimensional problem. When waveform data are used to invert for the source parameters, the solution is conditional under the influence of other unconstrained parameters. The trade-off problem between the parameters can be preponderant. It is, therefore, desirable to use a global optimization method to determine the source parameters in the whole parameter space. Our approach is to apply Genetic Algorithms (GA) to rapidly explore the model parameter space in search of optimal solutions that minimize the error between the observed and synthetic waveforms in a least squares sense.

Our data set consists of multi-station, broadband, teleseismic body waveform data. The source is defined by moment tensor (specified by scalar moment and the coefficients of five deviatoric elementary moment tensors), source-time trapezoid (rise and duration time), and depth. The near-source crustal structure is approximated with a few layers (specified by layer thicknesses and velocities) over a half-space.

In practice we first determine the moment tensor and source depth using constant source-time function and near-source structure. These parameters have larger effects on the waveform match. We then constrain the solution by allowing all parameters to vary in specified ranges. Results show that the GA solutions explain the waveform data better than published source parameter solutions and regional velocity models. The GA method can rapidly explore a large multiparameter model space to search for an optimal solution for the source parameters and constrain the near-source velocity structure without much a priori information.

ABOUT UTIG...

The Institute for Geophysics (UTIG), founded by Maurice Ewing in 1972, conducts geophysical investigations of the history, structure, and dynamics of the earth's crust, especially the ocean basins and margins, and of earthquake phenomena. The Institute is an Organized Research Unit established to serve the basic and applied geophysical research needs of The University of Texas at Austin. UTIG has evolved into one of the leading academic research groups in geology and geophysics.

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Institute capabilities in geophysical research extend from problem definition to data acquisition, data processing and, finally, interpretation of results. Development of new methodology and instrumentation for these studies is an integral part of the Institute's activities. To support research activities, UTIG provides a technical support staff to help with data processing, drafting, design and engineering, and to maintain equipment which includes low-fold multichannel systems, an array of active or passive ocean bottom seismometers, magnetometers, gravimeters and geothermal probes.

With a T1 connection to the The University of Texas at Austin Center for High Performance Computing (CHPC) Cray Y-MP8/864 computer, seismic reflection and refraction data is processed. UTIG has installed the Geovecteur software of CGG on the Cray allowing 2D and 3D seismic data processing and Geoquest™ interactive software mounted on color Sun Sparc™ hardware assists in 2-D and 3-D interpretation. UTIG currently has a network of 25 Sun™ workstations and 75 Macintosh™ computers , 7 laser printers and 1 Tectronics™ solid ink color printer. These are interconnected by AppleTalk™ and Ethernet™ with national and international connections to Internet and Bitnet. More than 20 Gbytes of disk is attached to the more powerful Suns, with 3 Gbytes concentrated on one Sun 4/380/32Mb server. This machine provides the services of many peripherals, including a 22 inch Versatec black and white plotter, a 34 inch Calcomp™ pen plotter, a 24 inch 4-color Versatec printer and 9-track and exabyte tape drives.

Research scientists often work as part of international and national teams in large, multi-disciplinary research programs. Disciplinary areas of research interests include seismic reflection and refraction, earthquake seismology, geothermal studies, gravity, geomagnetism, aerogeophysics, laser altimetry, geodesy, and theoretical geophysics. Geographic areas of research are worldwide.

While the work of the Institute is directed toward research, graduate student training is an important component of these activities. The Institute itself does not award degrees or offer formal classes for academic credit; rather the Institute maintains close relationships with the Department of Geological Sciences and the Marine Science Department. The Institute affiliates with these departments through cooperative programs and joint faculty appointments. Many geophysics graduate students at UT and other universities take advantage of the opportunity to work with the staff and facilities of the Institute for Geophysics. Graduate students are offered the opportunity to work on projects related to funded research programs. Office space and computational resources are made available to students in the Institute laboratory.

The Institute's laboratory is in north Austin near the University's J. J. Pickle Research Park. Further information regarding the Institute for Geophysics and its programs can be obtained from: Information Office, Institute for Geophysics, The University of Texas at Austin, 8701 N. Mopac Expressway, Austin, Texas 78759-8397. Phone: (512) 471-6156, Fax: (512) 471-8844, E-mail: utig@utig.ig.utexas.edu.

APPENDIX

Milestones in Marine Geophysics
September 28-29, 1994
Austin, Texas

Attendees

Institution	name
American Geophyscial Union	Fred Spilhaus
Amoco Production Co.	Mr. Gordon Greve
Amoco Production Co.	Wanda Greve
Arco Oil and Gas	Mr. Donald Dean
Columbia University	Dr. John C. Mutter
Exxon Exploration Co.	Dr. Arthur R. Green
HARC	Dr. Manik Talwani
HARC	Anni Talwani
JOI	Mr. Ralph Olmo
JOI	Mr. Terry Schaff
JOI, Inc.	Admiral James D. Watkins
NASA	Dr. Jim Heirtzler
National Research Council	Mary Hope Katsouros
National Science Foundation	Dr. James F. Hays
Natl. Taiwan Univ.	Dr. Allen T. Chen
NOAA R/OR1	Dr. Ned A. Ostenso
North Carolina State Univ.	Dr. Leonard J. Pietrafesa
Office of Naval Research	Dr. Fred E. Saalfeld
Palisades Geophysical Institute	Dr. H. James Dorman
Rice University	Dr. Dale S. Sawyer
Rice University	Elise Sawyer
Rutgers	Dr. Frederick Grassle
Shell Oil Co.	Dr. John A. Dunbar, Jr.
Southwestern University	Dr. Bill Obrien
Texas A&M University	Judy Rowe
Texas A&M University	Mrs. Feenan Jennings
Texas A&M University	Wilf Gardner
Texas A&M University	Feenan Jennings
Texas A&M University	Dr. Mary Jo Richardson
Texas A&M University	Dr. Gilbert T. Rowe
Texas A&M University	Dr. David A. Brooks
Texas A&M University	Dr. Robert Duce
Texas A&M University	Dr. William J. Merrell
Texas A&M University	Mary Duce
Texas Commerce Bank - Austin	Ms. B. J. Taylor
U.S. Geological Survey	Dr. John C. Behrendt
UCSD	Dr. Robert L. Fisher
UCSD	Dr. John Sclater
UCSD	Naila Sclater
UCSD	Sallie Fisher
UCSD	Gustaf Arrhenius
UCSD	Dr. Seiichi Nagihara
UCSD	Dr. John A. Orcutt
UCSD	Jenny Arrhenius
UNC at Wilmington	Dr. Marvin Moss
University of Cambridge	Dr. Dan McKenzie
University of Hawaii	Dr. Brian Taylor
University of Maryland	Dr. Donald F. Boesch
University of Miami	Dr. Bruce R. Rosendahl
University of Rhode Island	Dr. John A. Knauss
University of Rhode Island	Dr. Margaret Leinen
University of Washington	Dr. Arthur M. Nowell
UT-Arlington	Chris Scotese
UT Bureau of Economic Geology	Edmund G. Wermund
UT Center for Linear Dynamics	Harry Swinney
UTDGS	Martin B. Lagoe
UTDGS	Leon E. Long
UTDGS	Ernest L. Lundelius
UTDGS	Judy Lundelius
UTDGS	Michelle Kominz
UTDGS	Milo M. Backus
UTDGS	Robert E. Boyer
UTDGS	William D. Carlson
UTDGS	Mark Cloos
UTDGS	William L. Fisher
UTDGS	Wulf Gose
UTDGS	Stephen P. Grand
UTDGS	Mr. Fred Hutson
UTDGS	Dr. Earle McBride
UTDGS	Sharon Mosher
UTDGS	Amos Salvador

UTDGS	Sharon Mosher	UTIG	John Goff
UTDGS	Amos Salvador	UTIG	Kenneth H. Griffiths
UTDGS	Douglas Smith	UTIG	Judith A. Haller
UTDGS	James Sprinkle	UTIG	Leipin He
UTDGS	Ellin Wilson	UTIG	Ann H. Jessen
UTDGS	Barbara Backus	UTIG	Denise S. Kakas
UTDGS	Donna McBride	UTIG	Angelina Kennedy
UTDGS	G. K. Sprinkle	UTIG	Lis K. Könnecke
UTDGS	Sally Zellers	UTIG	Lawrence A. Lawver
UTDGS	Marilee Fisher	UTIG	Wayne L. Lloyd
UTDGS	Mark Helper	UTIG	Paul Mann
UTDGS	Jack Sharp	UTIG	Gyorgy Marton
UT Marine Science Institute	Terry Whitledge	UTIG	Chris Massell
UT-OSP	Wayne Kuenstler	UTIG	Kirk McIntosh
UT-OSP	Bobby C. McQuiston	UTIG	Brenda Meng
UTIG	Faruq Akbar	UTIG	Toni L. Mitchell
UTIG	Saif Al-Abri	UTIG	Kathryn A. Moser
UTIG	James A. Austin, Jr.	UTIG	Annejifke Mulder
UTIG	Nathan L. Bangs	UTIG	Yosio Nakamura
UTIG	Dan Barker	UTIG	Paul Nyffenegger
UTIG	E. William Behrens	UTIG	Charlene Palmer
UTIG	Janelle L. Berry	UTIG	Joseph D. Phillips
UTIG	Judeene. Blankenship	UTIG	Eleanor P. Picard
UTIG	Donald D. Blankenship	UTIG	Anita S. Rodriguez
UTIG	Thomas L. Bodine	UTIG	Luis Rodriguez
UTIG	Richard T. Buffler	UTIG	Judy Sansom
UTIG	Dee Dee Byers	UTIG	Steffen Saustrup
UTIG	Danielle Carpenter	UTIG	Mrinal K. Sen
UTIG	Gail Christeson	UTIG	Laurie Schuur
UTIG	Raghu Chunduru	UTIG	Krianti Setiyono
UTIG	Mike Coffin	UTIG	Samuel Sha
UTIG	Larry A. Cook	UTIG	Thomas A. Shipley
UTIG	Ian W.D. Dalziel	UTIG	Ben Sloan
UTIG	Thomas A. Davies	UTIG	Paul L. Stoffa
UTIG	Cliff Frohlich	UTIG	Pete Sweet
UTIG	Craig S. Fulthorpe	UTIG	Fumiko Tajima
UTIG	Lisa M. Gahagan	UTIG	Mahmet Tanis
UTIG	Patricia Ganey Curry	UTIG	Allison Teagan
UTIG	Jan Garmany	UTIG	Carlos Varela

UTIG	Mark Wiederspahn
UTIG	Charles C. Windisch
UTIG	Max E. Woyke
UTIG	Lian-She Zhao
UTIG	Ran Zhou
UTIG	Arthur E. Maxwell
UTIG	Alan Gahagan
UTIG	Alexandra Bangs
UTIG	Anne Nyffenegger
UTIG	Carolyn Sweet
UTIG	Colleen Maxwell
UTIG	Connie Bodine
UTIG	Don Palmer
UTIG	Donna Stoffa
UTIG	Ed Blankenship
UTIG	Gwendolyn Phillips
UTIG	Helen Griffiths
UTIG	Hiroko Nakamura
UTIG	Jackie Henkel
UTIG	Jill Kempf
UTIG	Joe Schedler
UTIG	Kelly Sommer
UTIG	Lila Beckley
UTIG	Linda Dalziel
UTIG	Linda Davies
UTIG	Linda Zhao
UTIG	Lucina Suarez
UTIG	Marjorie D. Mulanax
UTIG	Mrs. Carlos Varela
UTIG	Patricia Piceno
UTIG	Phil Sansom
UTIG	Robert Picard
UTIG	Shu-fen Sha
UTIG	Stanley Piatek
UTIG	Tam T. Le
UTIG	Tod Henning
UTIG	Toshi Tajima
WHOI	John I. Ewing
WHOI	Mr. Jake Peirson

WHOI	G. Michael Purdy
WHOI	Richard P. Von Herzen
WHOI	Betty Ewing
	Derek Barcinski
	John Burdine
	Mrs. Yvonne Burk
	Dr. Peter Gascoyne
	Richard A. Geyer
	Mr. Vance M. Lynch
	Delle Maxwell
	Gregory Maxwell
	Brett Maxwell
	Rick Maxwell
	Doris Rucker
	Leroy Rudder
	Mr. Carl Savit
	Sam Wade
	Henry S. Wade
	Gillian Wade
	Lynn Maxwell Gascoyne
	Maureen Barcinski
	Mrs. Carl Savit
	Mrs. Richard Geyer
	Mrs. Vance Lynch
	Phyllis Hasson